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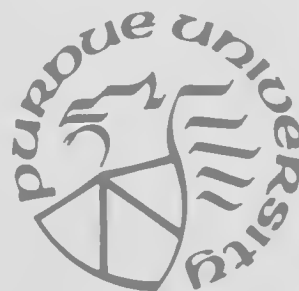
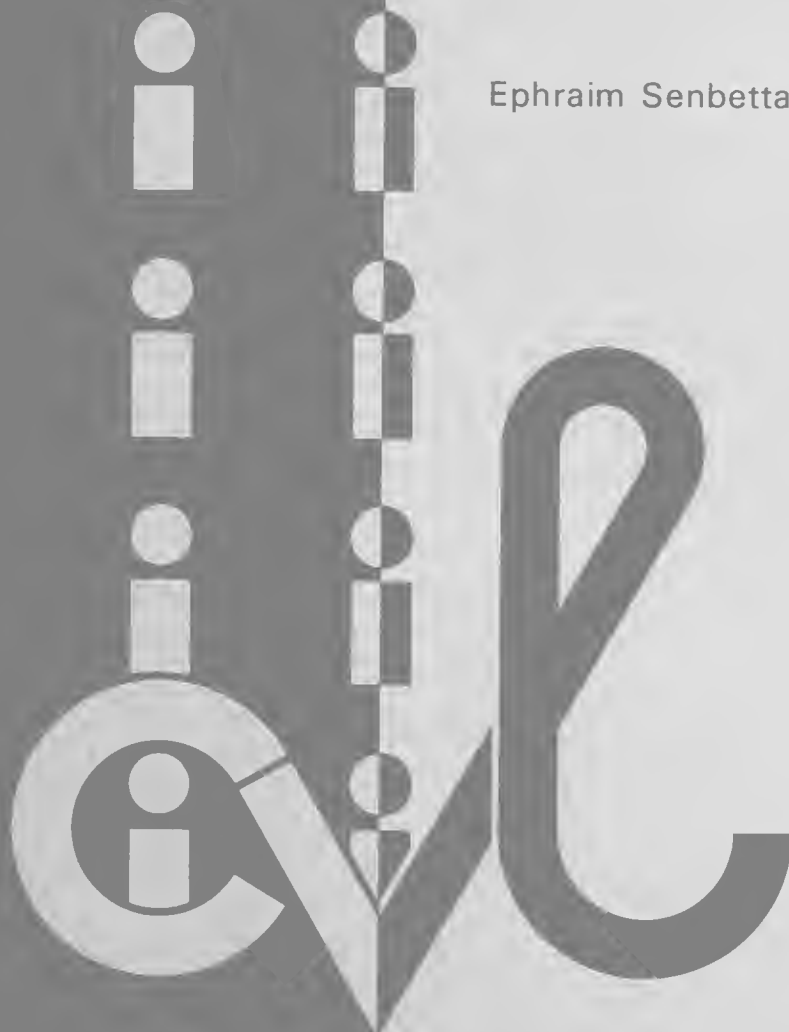


JOINT HIGHWAY RESEARCH PROJECT

JHRP-81-16

DEVELOPMENT OF A LABORATORY
TECHNIQUE TO QUANTIFY
CURING QUALITY

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Final Report
DEVELOPMENT OF A LABORATORY TECHNIQUE TO
QUANTIFY CURING QUALITY

TO: H. L. Michael, Director
Joint Highway Research Project

FROM: C. F. Scholer, Research Associate
Joint Highway Research Project

August 13, 1981

Project: C-36-65G

File: 5-15-7

The attached Final Report titled "Development of a Laboratory Technique to Quantify Curing Quality" is submitted on the JHRP research project on this topic. Mr. Ephraim Senbetta, Graduate Instructor in Research on our staff conducted the research and authored the report under my supervision and direction.

Although it is agreed that proper curing is essential if desirable qualities of concrete are to be realized, there is no satisfactory method by which a curing technique can be evaluated during or after the curing relative to the resulting quality of concrete. This research determined that an absorptivity test or an abrasion test were sensitive and reproducible indicators of the quality of cured mortar samples.

This Final Report is provided as fulfilling the objectives of the approved research and terminates the project.

Sincerely,

C. F. Scholer / ms

Charles F. Scholer
Research Associate

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Final Report
DEVELOPMENT OF A LABORATORY TECHNIQUE TO
QUANTIFY CURING QUALITY

by

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Joint Highway Research Project

Project No.: C-36-65G

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ABSTRACT

Senbetta, Ephraim. Ph.D., Purdue University, August 1981.
Development of A Laboratory Technique to Quantify Concrete
Curing Quality. Major Professor: Dr. C.F. Scholer.

Proper curing of newly placed concrete is essential if desirable qualities and expected durability of the hardened concrete are to be realized. Curing is particularly important for concrete structures such as pavements that have a large surface area. Review of the literature indicates that there is no satisfactory method by which the effectiveness of a certain curing method or material and the resulting quality of the concrete can be evaluated during or after the curing period. The indirect test methods used to evaluate the effectiveness of liquid membrane forming and sheet-like curing aids have been a subject of controversy owing to their inconsistency and lack of reproducibility.

This investigation was concerned with devising a direct, reliable, and sensitive test method by which the effectiveness of the curing of concrete can be evaluated. Being able to distinguish between well and poorly cured concrete by examining physical characteristics exhibited by the concrete in question is essential to control the quality of the curing process during construction and to identify curing related problems in concrete that is experiencing difficulty.

In this study mortar was used rather than concrete in order to maximize the amount of cement paste and to reduce the effect of the size of the aggregates on the relatively small test specimens.

The approach used consisted of making mortar slabs and subjecting them to widely different but controlled curing conditions that were thought to produce samples with different degrees of curing. The next step was determining appropriate test methods that are sensitive to small changes in the properties of the paste, as affected by the curing. The selected test methods were used on the samples, and a procedure was developed by which quantitative distinctions among the samples could be made.

The test methods selected were: The absorptivity test, which is indicative of the pore structure of the paste, non-evaporable water determination, which is an indicator of the extent of hydration of the cement, and the abrasion test (ASTM C418), which is a measure of the strength development of the surface region.

The absorptivity test and the abrasion test were found to be sensitive and reproducible indicators of the quality of the mortar samples. On the other hand, the non-evaporable water test did not produce the expected results.

The suggested method for distinguishing between adequate and inadequate curing involves changes in the absorptivity of the mortar in going from the surface to deep into the slab.

The test is quick and easy and reflects changes in the pore structure of the paste dependent on the severity of the exposure conditions and the extent of curing. Characteristic curves that show changes in the absorptivity of the mortar samples with depth were produced. The curves indicated significantly large changes in absorptivity in the case of poorly cured samples, and for the well cured samples the changes were negligible.

The dividing line between adequate and inadequate curing was based on differences between the absorptivity values at depths of 1 and 6 cm. It is suggested that a difference of $\leq 3.7 \times 10^{-6} \text{ cm}^2/\text{sec}$ is indicative of adequate curing, and a difference of $\geq 5.5 \times 10^{-6} \text{ cm}^2/\text{sec}$ corresponds to poor curing. The abrasion test results were in agreement with those of the absorptivity test, and there was good correlation between the two test results.

INTRODUCTION

Statement of the Problem

The influence of curing on the performance of concrete has been studied by many investigators, and it is believed that curing has a strong influence on the properties of hardened concrete. These properties include durability, strength, watertightness, wear resistance, volume stability, and resistance to freezing and thawing (1). Therefore, it is important to maintain for sufficient length of time favorable temperature and moisture conditions for proper hydration of the cement after concrete is placed and finished. In light of this, many methods and materials have been developed for curing concrete. There are also a variety of specifications that govern the various curing methods and materials.

Unfortunately, proper planning, design, and well-written specifications do not always guarantee the desired end product. Therefore, quality control tests are an indispensable part of concrete construction, and there are many such tests to assure uniformity and desirability of materials, desired properties of plastic concrete mixtures, and required strength of the hardened concrete. Although it is believed that curing is one of the most important steps in concrete

construction, and especially for unformed concrete structures such as pavements that have a large surface area in relation to depth, it is often one of the more neglected steps. And as important as the curing process is considered to be, there are no established methods for directly evaluating the effectiveness of a certain curing method and material and the resulting quality of the concrete.

Recognizing this need, in 1938 the director of Highway Research Board, Mr. Roy W. Crum, wrote:

...It has been found very difficult to distinguish at an early age between well and poorly cured concrete. Other things being equal, the range in quality is small at first and not easily measurable. Nor is it known with surety how great the range may be even toward the end of the useful life of the concrete when the maximum benefit from good curing should appear. It is evident that a method for comparing the relative values of different curing processes is greatly needed. Even more needed is a method of evaluating curing processes in general in relation to the quality of the concrete....

We should be able to analyze a sample of concrete, say at 7 days, chemically, physically, microscopically, or all three and tell whether or not it has been subjected to favorable influences during that period.... (2).

More than forty years have passed since this need was voiced, but review of the literature indicates that little has been done to develop a way of evaluating the effectiveness of a curing process in relation to the properties of the concrete. The study reported here was designed to identify and quantify properties of concrete that are indicative of the curing process and its effectiveness.

Statement of the Objective

As pointed out earlier, curing plays an important role in the production of durable, quality concrete. It is therefore desirable to have a method by which distinction can be made between well and poorly cured concrete. Such a method would enable one to not only control the quality of the curing process during construction but also to identify curing related problems in concrete that is experiencing surface problems.

The ultimate objective of the proposed research was to develop a method by which the effectiveness of the curing process can be evaluated in relation to significant physical properties of the concrete. In other words, a method was to be developed that would enable one to pick up a piece of concrete at a certain age and be able to say how well it was cured by running tests that are indicative of the quality of the curing process.

Literature Review

In this review the importance of the curing phase of concrete construction and the need for proper curing of concrete are discussed. The influence of weather conditions on the extent of effort that is required to achieve good curing is also considered. The review also contains an outline of various curing methods and materials, along with their respective advantages and disadvantages. In addition, a brief discussion of the problems involved with a standard test

method governing the various sheet-like and liquid concrete curing materials is given. Suggested test methods for determining the effectiveness of curing are also outlined, and finally, controversy surrounding the general subject matter of concrete curing is discussed.

By definition, curing of concrete is the maintenance of proper moisture and temperature conditions of newly placed concrete for a sufficient period to assure satisfactory hydration of the cementitious materials and proper hardening of the concrete. The definition contains four important factors that are a part of most studies dealing with curing of concrete. These factors are: maintenance of adequate moisture, proper temperature, a definite curing period, and the degree of hydration of the cement in the concrete. Maintaining proper moisture and temperature conditions is, in turn, related to the prevailing atmospheric condition which is another important factor in the study of curing of concrete.

It has been known that proper curing of concrete reduces shrinkage, accelerates strength gain, minimizes creep, improves durability, reduces efflorescence, improves abrasion resistance, and promotes impermeability. The most common shrinkage problem associated with curing of concrete is probably plastic shrinkage cracking. Although there are those (3) who believe that plastic shrinkage cracking is caused by differential settlement of fresh concrete due to obstructions to the settlement by large pieces of aggregates

and reinforcing steel, the widely accepted explanation to the cause of the problem is excessive drying in which the rate of evaporation from the surface of the fresh concrete is greater than the bleeding rate (4, 5). Too rapid a rate of moisture loss from a fresh concrete surface is also thought to be a cause for crazing (6). From the standpoint of the strength gain of concrete, it has been shown that the compressive strength, at 28 days, of uncured concrete is about half the strength of the same concrete if moist cured continuously for 28 days, and concrete that is moist cured for only three days and then left in air attains about 80% of its 28-day strength, whereas concrete cured for seven days and then left in air can achieve almost 95% of that strength (1). Although entrained air is considered to be the answer to freeze-thaw durability of concrete, studies done at PCA indicated that proper curing is indispensable for the development of a scale resistant concrete surface (4 p. 359). Proper curing also plays an important role from the standpoint of aesthetics by reducing efflorescence and surface discoloration (7). Abrasion resistance of a concrete surface has also been found to be greatly influenced by the effectiveness of the curing process (8, 9). In fact, the relationship between the two is so strong that abrasion tests are used as a relative measure of the effectiveness of the various curing methods and materials (10, 11). Finally, the watertightness of concrete is strongly influenced by the

curing of the concrete. It was shown that, for the same water-cement ratio, the permeability of a given concrete specimen was twice as much after three days of moist curing as it was after seven days (4 p. 363).

Although proper curing of concrete is essential, the extent of effort that goes into achieving it is dependent on the prevailing atmospheric conditions. It is obvious that a cloudy, windless, humid day with a temperature in the low 60's would be an ideal time for placing concrete, and not much effort would be required to obtain good curing. On the other hand, it takes a lot of effort to produce well cured concrete if the ambient relative humidity is low, the wind velocity is high, and the concrete and air temperatures are high. For example, when the relative humidity changes from 90 to 50%, the evaporation rate increases ninefold, and when both concrete and air temperatures go up from 50⁰F to 100⁰F, the evaporation rate increases about seven times. Also, it has been determined that when the wind velocity increases from 0 to 25 mph, the rate of evaporation increases by about nine times (4 p. 389, 5 p. 799).

A given curing method or material should, therefore, be able to counteract the negative effects of high temperature, low relative humidity, and high wind velocity. There are two methods by which favorable curing conditions can be provided. The first is by keeping the concrete wet by applying water, and the second is by keeping the concrete surface sealed, thereby preventing the loss of water. Ways

of applying water to a concrete surface include ponding, sprinkling, fogging, and spraying. Even though water is considered to be the most effective of all curing materials, it has several limitations. First of all, a large supply of water would have to be readily available, and constant supervision would be required to prevent drying out during the curing period. Also, water can not be used if the temperature goes down to freezing. In addition, curing with water is impractical for concrete surfaces that are not horizontal. To cure concrete by preventing loss of water, wet burlap, straw, hay, cotton mats, pads and quilts, earth, and sawdust covers have been used. These substances have the possible disadvantage of containing organic matter or other substances that would interfere with the setting of the concrete. They may also cause discoloration of the concrete surface (15). Other curing materials that require relatively less labor are paper and plastic (usually polyethylene sheet) covers, and membrane forming liquid curing compounds. Waterproof paper can either be a sandwich of paper-asphalt-paper or paper with plastic backing, and should comply with the requirements of ASTM C171 and C156. If such a paper has a white pigmented surface, it reduces absorption of heat and helps in maintaining temperature control of the concrete. Plastic sheets for curing concrete should also meet the requirements of ASTM C171 and C156, and they come in different colors and thicknesses. The one disadvantage

that is frequently mentioned with regard to the use of plastic sheets for curing concrete is that they can cause surface discoloration. Concrete surfaces that have been steel-troweled, and concrete mixtures containing calcium chloride are especially susceptible to this problem. Also a mottled appearance can result in cases where moisture condensation on the inside of a plastic sheet creased an uneven distribution of water on the concrete surface (4 p. 369, 12).

The most popular concrete curing method, especially for highway work, is the use of liquid membrane forming curing compounds. Their popularity is mainly due to their ease of application. These substances come in several colors including clear, white, and black, and they all have to comply with the requirements of ASTM C309 and C156. The usual application rates range from 150 to 200 sq. ft. per gallon, and although there is some controversy in the matter, the proper time for applying curing compound is usually when the free water on the surface of the concrete has disappeared and there is no more water sheen (12 p. 237, 13). The use of curing compound is not recommended where concrete is placed in the fall or winter in northern climates. This is because the concrete may not have an opportunity to air dry before freezing occurs and deicers are applied.

As stated earlier, liquid membrane-forming compounds and sheet like materials have to comply with the require-

ments of ASTM C156. The test is supposed to be a measure of their ability to prevent moisture loss from concrete during the early hardening period. There are also other tests such as the Canadian Government Specifications Board Standard 90-GP-1 and an AASHTO test (M-148) that are used to determine the water retention efficiency of certain concrete curing materials. Unfortunately, these tests have not been as reliable as they should be. Leitch and Laycraft (14) have found out that tests performed according to ASTM C156-65 and the Canadian test provide reproducible results only when carried out by a single operator. Results from different laboratories, and in some cases from different operators in the same laboratory, were found to have so much scatter that the results were meaningless. The same problem was noted by Spellman and Ford (15). In the case of ASTM C156 in particular, it is believed that the specification does not provide for adequate control over the effect of air circulation in the curing environment, and over the effects of sample preparation and surface texture.

The curing of concrete by preventing loss of the mix water may not be entirely adequate, in some cases, due to the self desiccating action of the cement in the mix. This means that drying of concrete can occur even though loss of water by evaporation is prevented. It is believed by several investigators (16, 17, 18) that concrete that is sealed to prevent evaporation must initially have a water-

cement ratio of about 0.53 to assure maximum cement hydration under sealed conditions. Because hydration is believed to take place only in water-filled spaces, as hydration proceeds, the water-filled spaces in a sealed specimen diminish more quickly than those in water-cured concrete. Besides, according to Powers (16), if the relative humidity in a concrete specimen drops to 80% or below cement hydration stops. Copeland and Bragg (18) have determined that for water-cement ratios of 0.53 and above, the effect of self desiccation is zero, but when the water-cement ratio is down to 0.44 it takes a sealed specimen one year to reach the same degree of hydration achieved by a moist-cured specimen in only 45 days. Therefore, curing by means of commercial sealing compounds has this limitation when applied to rich or dry mixes.

Owing to the fact that proper curing is an integral part of producing quality concrete, and because of the need for some sort of quality control on the efficiency of the curing procedure, several quality control measures have been suggested. One such test, referred to as "curing efficiency test", was suggested by Taylor (19). The test is supposed to be an efficiency index of membrane curing materials, and it involves flexure tests on beams (6 in x 6 in x 28 in). Test beams are cured for 28 days under three curing conditions: membrane, water, and air. The membrane and air cured specimens are supposed to be kept in a hot and dry

environment ($112^{\circ} \pm 2^{\circ}\text{F}$ and 17% R.H.), and the water cured specimens are kept at the same temperature but immersed in water. At the age of 28 days all the specimens are tested in a wet condition. The efficiency index is then calculated using the following expression:

$$\text{E.I.} = \frac{M - A}{W - A} \times 100$$

where M = average modulus of rupture for membrane cured specimens,

W = average modulus of rupture for water cured specimens, and

A = average modulus of rupture for air cured specimens.

If the E.I. is 60% or higher, it is supposed to indicate excellent curing and below 30% denotes poor curing. In the opinion of this investigator, there are reasons why this method is impractical for use as a quality control test of curing. First of all, it takes 28 days to find out the result, and secondly there is a question with regard to the sensitivity of modulus of rupture as a measure of the effect of curing. Because the test utilizes the entire specimen's strength, its sensitivity to slight changes in surface conditions is questionable. Besides, this test method does not involve specimens that are cured in the same natural environment as the concrete structure to be cured using the curing medium in question.

Even if approved methods and materials are used for curing concrete, there are times when situations arise that make it difficult to carry out the work as planned. A case in point is a problem that comes up in applying liquid curing compound at a prescribed rate on a concrete paving project on windy days. In situations like this, there is no way one can tell what effect inadequate coverage of the curing compound would have on the concrete. With this in mind Carrier (20, 21) developed a "curing-effectiveness gauge", which is also referred to as "relative humidity button". The device is a small plastic disc or "button" that contains chemical indicators that change color as the relative moisture content in the surface region of concrete changes. The disc is pressed onto the surface of newly placed concrete and curing compound is applied afterwards. Such a device is valuable, because it enables one to take corrective measures by calling attention to rapid drying of the concrete at an early age.

Another proposed method for determining the curing efficiency of concrete involves measuring the electrical resistance of the concrete (22, 23). An effective curing method is expected to hold the moisture in concrete, and the electrical resistance of concrete varies with the moisture content in the concrete. Therefore, electrical resistance measurements were used indirectly to make an assessment of the curing efficiency. The studies cited above that utilized this method were only concerned with a relative

measure of curing efficiency when different curing media are used, and their obvious shortcoming is that they did not give indications of what levels of resistance correspond to good or poor curing. They were also heavily influenced by abrupt changes in weather conditions such as a brief rain which may not have a lasting effect on the curing of the concrete.

In 1957 the Highway Research Board Committee on Curing of Concrete (24) proposed procedures that would provide data on the effects of various curing methods as applied under normal construction operation conditions. The recommended procedures were intended to provide information on the effect of curing on variations in concrete temperature during the curing period, strength of the concrete, and resistance of the concrete surface to frost action, abrasion, and other causes of surface disintegration. Although the recommendation utilized a realistic approach, it is too involved, and it is by no means a quick and easy way of evaluating the effectiveness of field curing methods.

Two insitu test methods that are supposed to be sensitive to variations in concrete quality and curing conditions were proposed by Johansen and Jorgensen (25, 26). Both methods can be used to test young concrete, and both involve and are correlated with the strength of the concrete. One of the test methods, known as the "Break-Off" method, utilizes a simple portable equipment marketed as "TNS-Tester". This

piece of equipment is used to determine the flexural strength of concrete in a plane parallel to and at a certain distance from a concrete surface. The test data available is all for tests done at a depth of 2.75". If the test can be performed successfully at shallower depths or closer to the surface of the concrete, the method has the potential to be useful for determining the effectiveness of concrete curing methods.

In 1953 a report (27) that summarized the replies to a questionnaire with regard to curing of concrete from 48 states and five federal agencies was published. The questionnaire was prepared to obtain information on such items as: permitted curing methods and the extent of their use, test methods and acceptance limits for liquid curing compounds, rate of application of curing compounds, orders of preference of curing methods and materials, criteria for opening of pavements, and so on. The responses indicated that there was substantial disagreement on most of the items in the questionnaire. Most of the disagreement was with regard to materials permitted for curing, extent of their use, duration of curing, types of curing compounds used along with their rate of application, their method of tests, and acceptance limits. There was also considerable lack of agreement on provisions governing the opening of pavements. The main conclusion that was reached from the survey was that the general subject matter dealing with curing of con-

crete was controversial. A review of the literature indicates that all the controversy has not yet been reflected in research effort designed to clear up the differences of opinion. An example of a more specific controversial issue is the question about how soon after concrete is placed should curing compound be applied. Burnett and Spindler (28) did a study on this topic and concluded that the optimum time for application of curing compound is at the time when the concrete reaches initial set. Their conclusion was based on the idea that delayed application of curing compound allows evaporation of mixing water while the concrete is still plastic thereby reducing the effective water-cement ratio at the surface of the concrete. Swayze (29, 30), and Shalon and Ravina (31) were also supportive of this notion. In fact, in addition to the strength gain that is achieved as a result of reduction of water-cement ratio, these investigators were of the opinion that evaporation of water up until the time when concrete ceases to be plastic contributes to surface densification as a result of forces due to capillary action and surface tension. Therefore, anything that causes the capillary pores to collapse before they become rigid, due to set, was considered useful, and the old-fashioned practice of rolling a concrete surface towards the end of the bleeding period was based on the same idea. On the other hand, Mather and Oleson (32), who wrote a discussion of the paper by Burnett and Spindler had a

serious concern about loss of water by evaporation from a fresh concrete surface after the water sheen caused by bleeding has disappeared from the surface. Their conclusion was that curing compound should be applied on a fresh concrete surface soon after surface moisture disappears by evaporation regardless of the set condition of the concrete.

In the opinion of this author, lack of tests to adequately evaluate the effectiveness of the various curing methods and materials has been the major cause of the uncertainty. Development of a direct approach for determining the quality of curing based on examination of the concrete that was subjected to a given form of curing may well be a less controversial and a more useful way of assessing how well concrete is cured, regardless of the method of curing. As pointed out earlier, one major deficiency of the state of the art at this time is that specifications dealing with curing of concrete focus on the acceptability of materials used for curing and not on the cured concrete. It is obvious that each method of curing is abused to varying degrees on actual construction projects. That is why effectiveness of curing should be evaluated by an examination of the cured concrete.

Approach Used in This Study

Mortar slabs were made and subjected to widely different but controlled curing conditions that varied from excellent to poor. Mortar was used instead of concrete because in-

cluding coarse aggregate in the mixes would have complicated the problem further, as will be shown later, and it would have reduced the amount of paste in the slabs. It was believed that understanding of the problem in its simpler aspects would clarify the more complicated conditions.

The next step in the study was determining appropriate test methods that are sensitive to small changes in the properties of paste that are affected by curing. Then the selected test methods were performed on samples taken from the carefully prepared mortar slabs. The data were statistically analyzed to develop a way by which quantitative distinctions between the various samples could be made.

EXPERIMENTAL WORK

Materials

Cement

Type I Portland cement with a designation No. 325 in the Joint Highway Research Project Concrete Laboratory at Purdue University was used. The physical and chemical properties of the cement are given in Tables 1 and 2 respectively.

Aggregates

Two types of fine aggregate were used. The first was a masonry sand obtained from a local gravel deposit. The masonry sand met the requirements of ASTM C144-76, which is the standard specification for aggregate for masonry mortar. Standard ASTM tests for gradation, dry rodded unit weight, specific gravity, and absorption were performed on the sand, and the results are presented in Table 3. The second type of fine aggregate used was graded natural silica sand from Ottawa, Illinois as specified in ASTM C778.

As stated earlier, coarse aggregate was not used for two reasons. First, using coarse aggregate would have introduced one more variable to be dealt with, and the problem would have been more complicated because of variations in

Table 1. Physical Properties of Cement*

Fineness, % passing #325 sieve	80.5
Specific surface, Blaine	3335 cm ² /g
Wagner	1750 cm ² /g
Initial set; Gilmore	1 hr., 40 min.
Vicat	80 min.
Final set; Gilmore	3 hrs., 40 min.
Vicat	170 min.
Normal consistency	24.5%
Autoclave expansion	.028%
Air entrained (ASTM C185)	8.0%

Compressive strength, psi:

1 day	2020
3 days	3300
7 days	4150
28 days	5330

*Data supplied by Lone Star Industries, Inc., of Greencastle, Indiana.

Table 2. Chemical Properties of Cement*

<u>Compound</u>	<u>% Present</u>
Silicon dioxide, SiO_2	21.12
Aluminum oxide, Al_2O_3	5.40
Ferric oxide, Fe_2O_3	2.27
Calcium oxide, CaO	65.24
Magnesium oxide, MgO	1.22
Sulfur trioxide, SO_3	2.97
Potassium oxide, K_2O	0.78
Loss on ignition	0.80

Calculated Compound Composition

<u>Compound</u>	<u>% Present</u>
Tricalcium silicate, C_3S	57.0
Dicalcium silicate, C_2S	17.6
Tricalcium aluminate, C_3A	10.5
Tetracalcium alumino-ferrite, C_4AF	6.9

*Data supplied by Lone Star Industries, Inc., of Greencastle, Indiana.

Table 3. Gradation and Properties of Regular Masonry Sand

<u>Gradation</u>	
<u>Sieve size</u>	<u>Cumulative % retained</u>
#4	0.5
#8	2.6
#16	14.3
#30	37.1
#50	82.2
#100	98.4

Fineness modulus = 2.35

<u>Properties</u>	
Dry rodded unit weight	= 108 lb/cu. ft.
Bulk specific gravity	= 2.54
Bulk specific gravity (SSD)	= 2.58
Apparent specific gravity	= 2.65
Absorption	= 1.6%

the type and size of the aggregates. Secondly, the use of coarse aggregate was not desirable, because the amount of paste in the mix would have been less than what it would have been without the coarse aggregate. And finally, the effect of aggregate size on small test samples is reduced by dealing with mortar rather than concrete. The interaction of paste and aggregate is an important factor to be considered in both fresh and hardened concrete, but in addition to the reasons given above, a mixture with a maximum amount of paste was thought to be desirable for this study because the paste is the component that is affected by the curing process.

Water

Ordinary tap was used as mixing water in all the mixes. The temperature of the water was maintained at approximately 20°C (68°F).

Curing Compound

One of the curing methods used was the application of a curing compound. The curing compound used was a clear or translucent type, with a Type 1 designation according to ASTM C309. It was supposed to be applied on the surface as soon as bleed water disappeared. According to the manufacturer, the curing compound could be sprayed, brushed, or rolled on the surface.

During the testing phase of the study it was discovered that the curing compound was not effective, and a test done

by the Indiana State Highway Commission Materials Testing Laboratory revealed that the curing compound did not pass the ASTM standard test method for water retention by concrete curing materials. It is not known why the curing compound did not pass the test in spite of the manufacturer's claim to the contrary. It is interesting to note that the test method developed by this study did signal the inadequacy of this particular curing method at an early age. In fact, the efficiency of the curing compound was questioned, and its effectiveness tested after evaluation of the cured mortar samples signaled poor curing. This particular problem is a case in point for the usefulness of the type of curing efficiency test addressed by this study.

Sample Preparation

Environmental and Curing Conditions

Most of the slabs for this study were batched, cast and cured in a large environmental chamber that was available for a limited amount of time. It had a total volume of approximately 5000 cu ft, and had excellent temperature ($\pm 1^{\circ}\text{C}$) and humidity ($\pm 2\%$) controls. Conditioned air was introduced into the chamber at a rate of 10,000 cu ft per minute. This meant that the air in the room changed every half minute. Also, because the conditioned air was blown into the room via ports spread throughout the ceiling, there was no air turbulence.

Because of the time constraint involved in the use of the environmental chamber, all the slabs had to be made and cured within a period of three weeks. Therefore, the plan called for a maximum curing period of five days and one temperature-humidity condition for each of the three weeks. A decision was made to keep the chamber temperature constant at 27°C (81°F), and to vary only the relative humidity. So, for samples made and cured during the first week, the relative humidity was set at approximately 22%, for the second week at 44%, and for the third week at 72%. These three levels were chosen to create environmental conditions that would bring about different rates of evaporation of water from the newly placed mortar slabs. In addition to the prevailing temperature and relative humidity conditions, in one part of the chamber an oscillating fan was set up to create windy atmosphere at each of the three temperature-humidity conditions. The fan delivered a gusty wind of approximately seven miles per hour. By introducing wind with each temperature-humidity condition, it was possible to add three different rates of evaporation. All in all, there were six atmospheric conditions causing six different rates of evaporation of water from the fresh mortar surfaces. Table 4 shows these six atmospheric conditions and the corresponding rates of evaporation.

In addition to the six atmospheric conditions, five curing conditions were used in the study. The five curing conditions were:

1. Covering the slabs completely with plastic sheet when bleed water disappeared from the surface. This curing condition will be referred to as PL.

2. Covering the slabs with a double layer of wet burlap when bleed water disappeared. The burlap was wetted twice a day, and this curing condition will be referred to as WB.

3. Applying curing compound when bleed water disappeared. The curing compound was applied at a rate of approximately 150 ft^2 per gallon. This curing condition is given the designation CC.

4. Leaving the slabs exposed to the prevailing atmospheric conditions without any cover. This condition will be referred to as EX.

5. Same as number 4 except in this case the slabs were kept exposed in a windy atmosphere, and this curing condition will be referred to as EW.

Table 4. Rates of Evaporation Caused by Six Atmospheric Conditions

<u>Atmospheric Conditions</u>	<u>Rate of Evaporation* (lb/hr/ft^2)</u>
22% RH with wind	0.1025
44% RH " "	0.0838
72% RH " "	0.0441
22% RH without wind	0.0225
44% RH " "	0.0165
72% RH " "	0.0093

*The rates of evaporation were from free water surface

A third variable in the study was duration of curing or age. Owing to limitation of time and handling problems, the effect of age was examined for only one of the five curing conditions, where wet burlap (WB) was utilized. Because the focus of the study was on paste properties at early ages as affected by curing, three short durations of curing were selected. The three were, 1 day, 3 days and 5 days.

Table 5 shows the layout of the various samples made under the different curing conditions and durations described above. The symbols used in the table will be used throughout this report, and it is important to note their inter-

Table 5. Layout and Designation of Samples Made Under the Various Curing Conditions and Durations

Relative Humidity	With Wind	Without Wind
22%	EW5	WB5, WB3, WB1 CC5 PL5 EX5
44%	EW5	WB5, WB3, WB1 CC5 PL5 EX5
72%	EW5	WB5, WB3, WB1 CC5 PL5 EX5

Note: As stated earlier, each alphanumeric symbol stands for the method and duration of curing. For example, WB1 represents curing with wet burlap for one day. PL, CC, EX and EW stand for plastic cover, curing compound, exposed, and exposed with wind respectively.

pretation. Each alphanumeric symbol represents a given curing condition and duration of curing. For example, PL5 represents curing with plastic cover for five days, and WB1 stands for curing with wet burlap for 1 day, and so on.

Table 5 shows that for each relative humidity condition seven slabs were made. However, it should be noted that three times that many slabs were prepared, because duplicate samples were made using the regular masonry sand, and in addition, for each humidity and curing condition, as well as age, slabs with silica sand were prepared.

The reason for making duplicate slabs using the regular masonry sand was in order to test the first set soon after the end of each of the three curing periods, and the second set three months later. During the three months, the slabs were subjected to wetting and drying cycles similar to those a pavement exposed to rainy and dry atmospheric conditions would experience. It was thus possible to see the effect of the initial curing condition on paste properties at a later age. In order to have controlled wetting and drying, the slabs were put in a fog room at 21°C (70°F), for two days each time, starting 12 days after the end of the curing periods. After two days in the fog room the samples were taken out of the room and left in the lab for 14 days before being put back in the fog room for 2 more days. Within a period of two months, the samples were put in the fog room three times. At the age of three months

the samples were tested in the same manner as the first set of slabs that were tested soon after the end of their curing periods.

Details of the process of making both the slabs made of ordinary masonry sand, and the slabs made of the graded silica sand from Ottawa, Illinois will be described next. All slabs had the same water to cement ratio of 0.5, and a sand to cement ratio of 2.7.

Preparation of Regular Masonry Sand Slabs

Three batches of mortar were mixed during each of three days of mixing, for each relative humidity condition, and a total of fourteen slabs were cast. The mix proportions for each batch were:

sand	-	123.3 lb
cement	-	45.0 lb
water	-	24.0 lb*

Each batch was just enough to make five 14 in. x 10 in. x 3½ in. slabs. The mixer used was a 4½ cu ft absolute capacity drum mixer. It had a one half horsepower electric motor that turned the mixer at a rate of 20 revolutions per minute.

The mixing procedure was as follows: To start with, the mixer was wetted and all excess water drained. Then, all the sand was put in the mixer along with approximately half of the mix water and mixed for one minute. Next, all

*Includes water to compensate for absorption because oven-dried sand was used.

of the cement was added and mixed for one more minute. Then, the rest of the mix water was added, and mixing was continued for two more minutes. This was followed by a rest period of one and one half minutes, and then by one minute of final mixing. When the mixing was completed, the fresh mortar was dumped in a large pan.

Clear, one piece, plastic molds 14 in. x 10 in. x $3\frac{1}{2}$ in. were used to form the slabs. In casting the slabs, each plastic mold was placed on top of a 14 in. x 20 in. plywood board ($\frac{1}{2}$ in. thick) and put on a 20 in. square vibrating table. Then, the mold was filled with the fresh mortar and vibrated for 15 seconds. The vibrating table vibrated in the vertical direction at a rate of 3600 cycles per minute, and the control knob for the amplitude was set on "eight". The table was manufactured by FMC Corporation and its model number was V51C1.

Immediately after the mortar was consolidated by vibration the surface was screeded and smoothed using a one inch diameter smooth plastic rod (21 in. long). The rod was held down against the mold and moved across the surface of the fresh mortar several times with a sawing motion. See Figure 1. Once a smooth surface was obtained, no additional manipulation or finishing was given to the surface. The slab was then placed on a rack in the environmental chamber. All the slabs were distributed throughout the chamber, and the slabs that were exposed to wind were put on a rack in



FIG. 1 SLAB CASTING PROCEDURE.

front of one of the exhaust vents with an oscillating fan on the opposite side of the vent about 6 ft away from them. As stated earlier the fan was producing wind that may be considered gusty with maximum wind speed of about 7 mph.

In addition to the 14 in. x 10 in. x 3½ in. slabs, six 3 in. by 6 in. cylinders were made from the third batch of each of the three days of mixing. The cylinders were cured in a fog room for 28 days, and were tested in compression.

Preparation of Silica Sand Slabs

It was learned from trial mixes that the drum mixer and the mixing procedure used for the masonry sand mixes were not suitable for mixes with the much finer silica sand. Trial mixes done using the drum mixer produced non-homogeneous mixtures containing balls of cement paste. Also, only half as many slabs were made using the silica sand, and the surface area of the slabs was smaller. Therefore, a different type of mixer and mixing procedure were used. The mixer used was a Hobart Model A-200 with a 20 quart capacity bowl. All the mixing was done at low speed with agitator speed of 107 revolutions per minute.

At each of the three relative humidity conditions eight 12 1/4 in. x 6½ in. x 3½ in. slabs were made. Owing to the size of the mixer, one batch, that was enough to make the eight slabs, consisted of three separate mixes combined together. The mix proportions for each mix were as follows:

sand - 37.0 lb
cement - 13.5 lb
water - 6.8 lb

The mixing procedure consisted of the following steps: first the bowl was wetted and all excess water removed. Then all of the mix water and all of the cement were put in the bowl and mixed for one minute. Next, the sand was added gradually and mixed for one and one half minutes, and then the mix was allowed to rest for one and one half minutes, followed by one more minute of final mixing.

Because each mix was only one third of a batch, at the end of the mixing period the mix was put in a large pan and covered with plastic sheet until all three mixes were completed. These were then combined by using a shovel.

For casting the slabs, using 12 1/4 in. x 6 1/2 in. x 3 1/2 in. plastic molds, the procedure was the same as for the slabs made of the masonry sand.

Preparation and Preservation of Test Specimens

There was one problem caused by the fact that the test slabs had to be produced within a short period of time. Because preparing the individual test specimens and doing the various tests took a lot longer than making the slabs, it was necessary to determine an effective method by which the test specimens could be preserved in the same condition they were at the end of their respective curing periods.

The method that was found suitable for this purpose was soaking the test specimens in methanol. It has been determined in the course of this study that allowing methanol to penetrate the pores of cement paste prevents further hydration of unhydrated cement in the paste. Absorptivity tests done on the original samples and on companion samples that soaked in methanol for as long as three months produced essentially the same result. All the samples were either sawed or cored in such a way that they had a maximum thickness of about one and one half inches before they were put in baths of methanol. It was believed that keeping the maximum thickness small would allow the methanol to saturate the pores in a reasonably short time.

The test specimens were for the most part one inch diameter cores that were later sliced to give one centimeter thick disks. The cores were taken using $1\frac{1}{2}$ in. outside diameter standard diamond core drills manufactured by Felker Manufacturing Company, Torrance, California. In the coring process ordinary tap water was used as a coolant. The coring was done rapidly to minimize the amount of water absorbed by the mortar, and as soon as a core was taken all excess water was wiped from its surface, and it was immersed in methanol. In addition to the cores, other pieces of mortar $3\frac{1}{2}$ in. by about 5 in. ($1\frac{1}{2}$ in. thick) were kept in jars of methanol.

Further handling of the test specimens will be described in conjunction with the various test procedures.

Test Procedures

Introduction

In the process of determining test methods that are sensitive to small changes in paste properties as affected by curing, several types of tests were reviewed and/or tried. Among these test methods were: pulse velocity measurements (ASTM C597), the use of rebound hammer (ASTM C805), petrographic examination of polished surfaces to determine the amount of unhydrated cement, several different types of permeability of absorption tests such as the British test for determining the initial surface absorption of concrete (33), Figg's method for measuring the air and water permeability of concrete (34), hardness test using the Rockwell hardness tester, and mercury intrusion porosimetry. None of the above was selected for use in this study because they were thought to be either not sensitive enough or too cumbersome for their intended purpose.

After reviewing a list of possible test methods, the following three methods were selected and used:

1. Absorptivity test, which is indicative of the pore structure of cement paste, and of microcracking.
2. Non-evaporable water determination to determine the extent of hydration of the cement for a given condition and

duration of curing.

3. Abrasion test according to ASTM C418-76, which is abrasion by sandblasting.

The rationale behind the use of the above test methods was as follows. No matter how poor the curing conditions may be, the bottom of a slab is not affected nearly as much as the surface, as long as the slab is not extremely thin. Therefore, it is reasonable to expect a certain characteristic change in paste properties with depth, for a given curing condition and duration of curing. So, it is thought that effectiveness of curing should be evaluated based on the behavior of the entire thickness or at least a portion of the thickness affected by the curing rather than just the surface. Consequently, the tests, except for the abrasion test, were performed on samples taken from the various depths of the total thickness of each of the 3.5 in. thick slabs. This procedure was also thought to give an indication of the depth to which poor curing has an effect. In other words, how much of the entire thickness of a concrete slab is influenced by poor curing can be determined.

Absorptivity Test

This is a simple test that was devised and used by Powers and Brownyard on hardened cement paste (35), and later used by Dolch in a study of the pore structure of Indiana limestone coarse aggregates (36). According to Powers and Brownyard, the term "absorptivity" pertains to the character-

istic rate at which a dry or partially dry sample absorbs water without the presence of any hydraulic pressure. It is strictly a measure of capillary absorption. The procedure used to do the test greatly influences the results. The initial state of the test sample and its uniformity of dryness alone play a large role in the outcome of the test results. Other factors which have a significant influence are thought to be: the curing history, water-cement ratio, aggregate characteristics (absorbent or not), air content, cement type and fineness (especially at early ages), specimen size and shape, method of surface preparation or surface texture and surface carbonation (37).

It is known that a sample of cement paste maintains the same external volume during the hydration process, but within the sample itself the volume of solids increases. This in turn is the cause for the reduction of the porosity of the paste (38). Therefore, if concrete is subjected to good curing for a given length of time its porosity can be expected to be less than that of a similar concrete sample that was not cured properly during the specified curing period.

Absorptivity depends on porosity, size of pores and microcracking. The coefficient of absorptivity, K_a is defined by

$$\left(\frac{V}{A}\right)^2 = K_a t \quad (1)$$

where $\frac{V}{A}$ = volume of water per unit cross sectional area absorbed in elapsed time t

K_a = coefficient of absorptivity

The test was done in the following manner. A one inch diameter core was taken out of a bath of methanol where it was stored, and the top 1 mm of the core was cut off and discarded. Then, the rest of the core was sliced into several 1 cm thick disks. The cutting was done using an Isomet low speed saw equipped with a low concentration diamond blade. In the cutting process, ethanol was used as a coolant, and the core was never in contact with water. When the core was sliced, each disk was marked on its side to indicate its top cross section, which was subsequently tested after drying. From a 3.5 in. long core, eight disks were obtained, and on the back side of each disk a number was written to indicate from what depth the disk was obtained. The cut surfaces had a virtually polished texture. Figure 2 shows the equipment.

Soon after the slicing of each core was completed, the small disks were dried at room temperature using a special process that was determined to be effective. As shown on Figure 3, the disks were put in a desiccator, and the desiccator was connected to a vacuum pump for approximately 48 hours. The vacuum in the desiccator was kept at approximately 19 torrs as determined by a manometer. That method of drying was an efficient way of emptying the pores in the

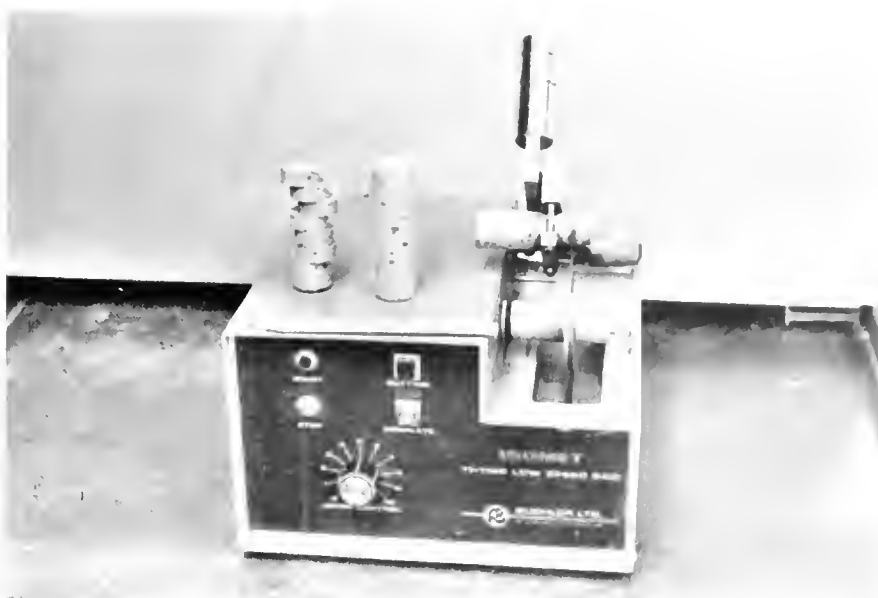


FIG. 2 CORE SLICING EQUIPMENT.

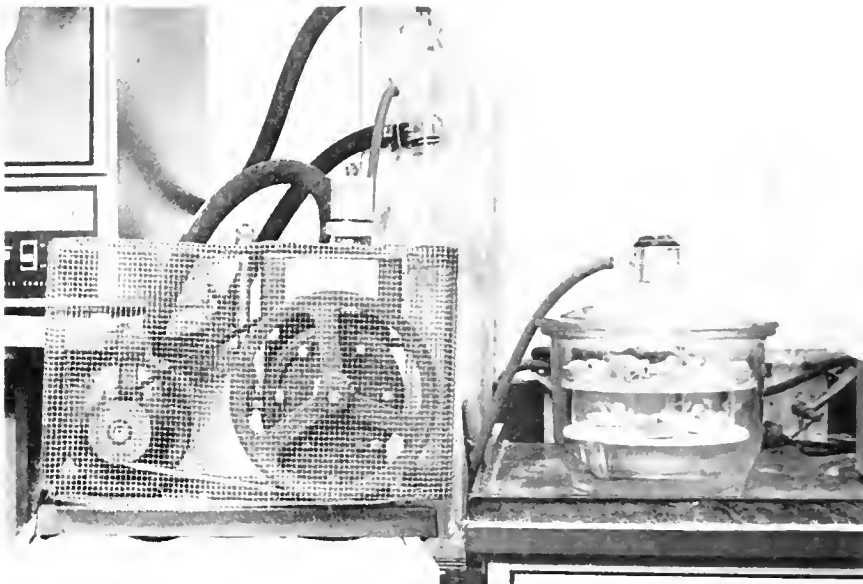


FIG. 3 DRYING APPARATUS.

cement paste without causing cracking. Other methods of drying were tried but none was better because in each case high absorptivity value resulted owing to the presence of microcracks. Oven drying at temperatures as low as 60°C was found to alter the samples by introducing microcracks. Also the effect of heat was not the same on all disks. For a disk obtained from near the top of a poorly cured sample, the effect of heat was minimal, but for disks from deeper zones, the effect of heat was pronounced. Therefore, drying under vacuum at room temperature was the best method to have the capillary pores at least partially dry. The duration of drying was arbitrarily chosen, but it is believed that drying for a shorter period of time would not empty the pores adequately and drying for longer periods would lengthen the time to do the test without any apparent benefit.

Once the disks were dried, the actual testing process followed. The test involved: first, weighing a disk dry, and then bringing the top surface of the disk in contact with a free water surface for several one minute intervals of time and weighing the disk at the end of each minute to determine the amount of water absorbed per unit time. It took approximately 26 seconds to pick up a disk from the free water surface, blot off excess water from the surface of the disk using damp tissue paper, weigh the disk, and put it back on the free water surface. What was considered to be a free water surface was obtained by putting a stack of

eight pieces of filter paper in an evaporating dish and wetting the filter paper using deionized water at approximately 21°C (70°F). The amount of water was enough to thoroughly wet the stack of filter paper with some extra water left. Too much excess water caused a sloppy filter paper that wetted the sides of the disks. While a disk was in contact with the wet filter paper, it was covered by a small glass jar to prevent evaporation of absorbed water from the disk. The glass jar had a diameter of approximately an inch and half and it was about two inches high. All the weighings were done to the nearest 0.0001g on an analytical balance. See Figures 4 and 5 for the absorptivity test setup.

The data were then plotted on log-log paper, V/A on the y-axis and time, t , on the x-axis. According to the theory such a plot should give a straight line with a slope of one half if the flow of water in the porous medium follows the relationship given by Equation 1. Many such plots were made, and it was confirmed that when the testing procedure, as explained above, was used on the mortar disks, the water flow in the pores of the mortar did follow the relationship given by Equation 1. From then on, the testing was done for only one minute on each disk. A plot of $\log V/A$ vs $\log t$ for tests done on the various slices of a core is shown on Figure 6.



FIG. 4 ABSORPTIVITY TEST APPARATUS.



**FIG. 5 ABSORPTIVITY TEST SPECIMEN
IN CONTACT WITH A FREE WATER
SURFACE.**

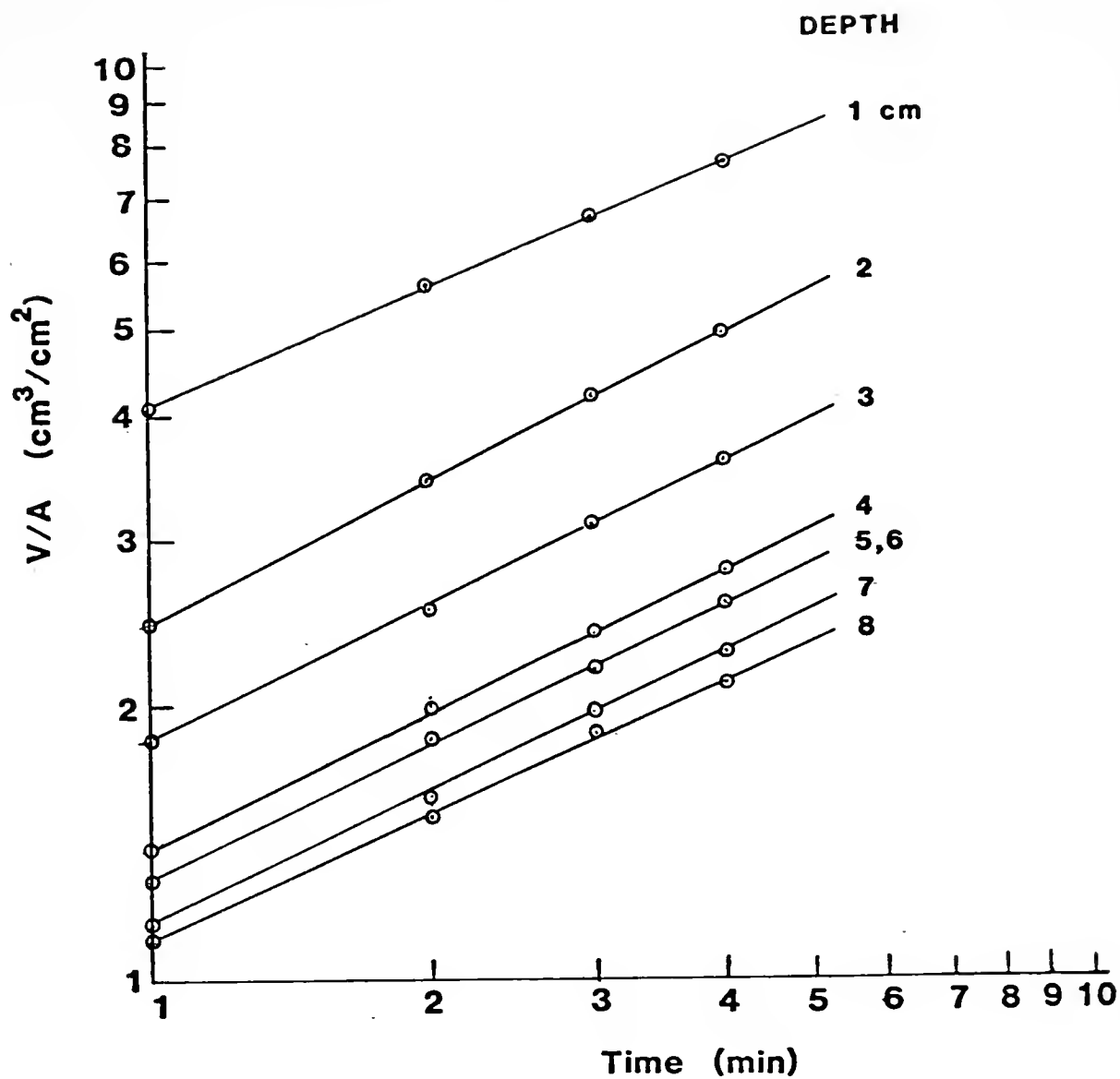


FIG. 6 ABSORPTIVITY AT VARIOUS DEPTHS OF MORTAR SAMPLE MADE WITH REGULAR SAND AND CURED EXPOSED AT 22% R.H. FOR 5 DAYS.

Non-evaporable Water Determination

To a large extent proper curing of concrete involves maintaining adequate moisture in the concrete so that hydration of the cement can continue without interruption. Therefore, for a given concrete sample, determining the extent of hydration over a given length of time can be a reflection of the effectiveness of the curing process.

Water in hydrated cement is arbitrarily divided into two categories: evaporable and non-evaporable. Evaporable water is determined by drying cement paste to constant weight in a specified manner. There are several ways of doing such drying: (a) P-drying at a given vapor pressure of 8×10^{-3} mm of mercury, using $\text{Mg}(\text{ClO}_4)_2 \cdot 2\text{H}_2\text{O}$, (b) D-drying in vacuum connected to a cold finger held at -79°C , and (c) oven drying usually at 105°C (6 p. 35). The standard way of determining non-evaporable water is by igniting the cement paste at 1050°C to constant weight after the sample is dried by means of one of the above methods, and all the evaporable water has been removed. Non-evaporable water is normally expressed in terms of grams of water per gram of the original dry cement (39). It has been determined that in well hydrated cement 18 percent by weight of the dry cement is non-evaporable water, and this percentage goes up to 23 percent in a case of fully hydrated cement (6 p. 36). This relationship between the amount of non-evaporable water and the anhydrous cement is what makes it possible to use the amount of non-evaporable water as a measure of degree of hydration.

This idea was used in this study as follows. As was done with the absorptivity test, one inch diameter cores which were stored in a bath of methanol were used, and the cores were sliced in the same manner as before. The 1 cm thick disks were then dried in an oven at 105°C for 24 hours to remove the evaporable water.

For samples made with pure silica sand, the non-evaporable water was determined by igniting the oven dried disks in a muffle furnace at 1050°C . In this study non-evaporable water was expressed as percent by weight of oven dried mortar. For samples made with regular masonry sand that contained carbonate rocks which would decompose at 1050°C , a lower temperature that would not affect the carbonates but was high enough to remove most of the chemically bound or non-evaporable water had to be determined.

For this purpose, samples of reagent $\text{Ca}(\text{OH})_2$, reagent CaCO_3 , mature cement paste (12 years in lime water), and the local masonry sand were used. The sand and paste samples were dried in an oven at 105°C , allowed to cool in a desiccator, and weighed on an analytical balance. Then, two samples from each of the above four materials were put in crucibles, weighed, and heated for four hours each at 550°C , 600°C , 650°C and 700°C . The samples were allowed to cool in a desiccator and weighed after being heated at each of the four temperatures. The result, as shown on Table 6, led to the conclusion that heating at 550°C was the most appropriate

temperature for determining non-evaporable water of the mortar samples made with regular sand. Temperatures below 550°C were not used because 522°C is the temperature at which $\text{Ca}(\text{OH})_2$ decomposes (40). Since calcium hydroxide is one of the hydration products of cement, going to a lower temperature would not have insured its decomposition.

Table 6. Weight Loss on Heating

Sample	% Weight Loss at Given Temperature*			
	550°C	600°C	700°C	750°C
$\text{Ca}(\text{OH})_2$	22.73	22.50	22.86	22.16
CaCO_3	.27	1.41	7.15'	27.68'
Local Masonry Sand	1.13	1.81	3.29	7.92
Mature Cement Paste	14.92	15.85	16.35	16.49

*All percentages by weight of the original dry samples, and average of two observations.

'Single value, not average

Non-evaporable water for all samples made of the regular masonry sand was determined by heating the small disks at 550°C for approximately four hours after all the evaporable water had been driven off by oven drying at 105°C .

Abrasion Test

It is well known that abrasion resistance of concrete depends mainly on the mix, placing, finishing, and curing

and of these four, it is said that curing is probably the most important factor (41). One of the adverse effects of poor curing of concrete is low strength and also low abrasion resistance. In fact, it has been shown that the abrasion resistance of ordinary concrete is proportional to its compressive strength at the exposed surface (42).

According to Prior (41 p. 247), there are four types of wear of concrete surface by abrasion. The first type is, abrasion due to a rubbing action as is the case where skidding, scraping, or sliding of light objects such as small vehicles is involved. The second type is, wear due to rubbing action plus impact in the presence of heavy vehicles with or without chains. The third, involves hydraulic structures such as dams and spillways, and the type of wear is one due to the cutting action of abrasive particles carried by flowing water. And, the fourth type of wear is cavitation erosion involving hydraulic structures.

There are also different types of machines used to simulate the various conditions that bring about wear of concrete surfaces. The abrasion test method used in this study is a standard ASTM test (C 418-76) for abrasion resistance of concrete by sandblasting, and according to the standard, this method of test simulates abrasion wear of concrete surfaces due to the action of waterborne abrasives, and abrasion under traffic.

The abrasion test was performed according to ASTM

C 418-76 with only one exception. The samples were immersed in water for only five hours before they were blasted instead of the recommended 24 hours. This was to avoid any further significant hydration and strength gain. Preliminary trials indicated that five hours was long enough to saturate the surface regions of the slabs.

The test was done on all the large slabs made with regular masonry sand and only on a few slabs made with silica sand. Before testing the large (10 in. by 14 in.) slabs, each was cut leaving a surface of 8.5 in. by 10 in. for the abrasion test. The other piece from each slab was put in methanol after it was cored and sliced to be used for other tests. Each of the test pieces was then soaked in lime water at approximately 21°C for five hours and blasted at eight different spots on the surface. The surface of each slab was kept normal to the axis of the nozzle at a distance of 3 ± 0.1 in., and each randomly selected spot was blasted for one minute. The air pressure at the nozzle was kept at 60 psi, and the flow rate of the abrasive material was 600 ± 25 grams per minutes. The abrasive was 20-30 Ottawa sand.

For the purpose of adjusting the nozzle-to-sample distance and for leveling the sample, a special platform with adjustable height and leveling screws was fabricated and used. Also, a bull's eye level was used to insure the horizontality of the surface to be blasted. See Figure 7 for the abrasion test setup.

After blasting all eight spots on the surface of each slab, a felt-tipped pen was used to draw an outline of each of the blasted spots. Then, according to the recommendations of ASTM C 418-76, each blasted cavity was filled with an oil base modeling clay to determine its volume. The modeling clay had a specific gravity of 1.59. Figure 8 shows the appearance of the sandblasted abrasion test samples, and on Figure 9, the method used for determining the volume of the abraded cavities can be seen.

For the purpose of quantifying the abrasion loss suffered by a test specimen, the ASTM standard recommends expressing abrasion loss in terms of abraded volume in cm^3 divided by the abraded area in cm^2 to the nearest $0.01 \text{ cm}^3/\text{cm}^2$. In essence, this is the same as expressing abrasion loss in terms of average depth of the abraded cavity, but this was not appropriate for the problem on hand. If the abraded area was constant in all cases, average depth would have been a suitable parameter. In this study, the samples that experienced the least abrasion loss also had a small abraded area, and the poorly cured ones with a poor quality surface, suffered high abrasion loss accompanied by a large abraded area. Therefore, volume/area for the two samples was nearly the same. For this reason, it was decided to express abrasion loss of a sample in terms of the average volume in cm^3 of the eight abraded cavities.

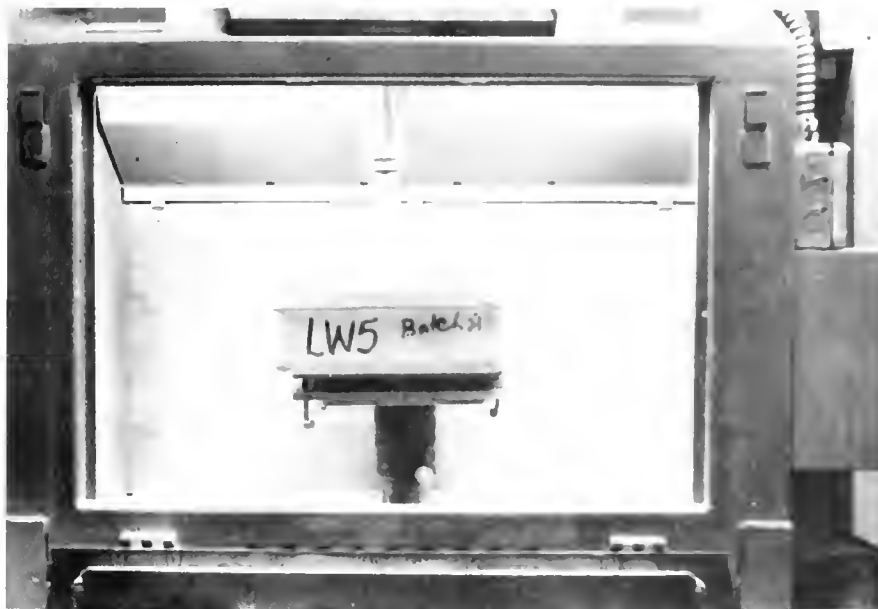


FIG. 7 ABRASION TEST SET UP.

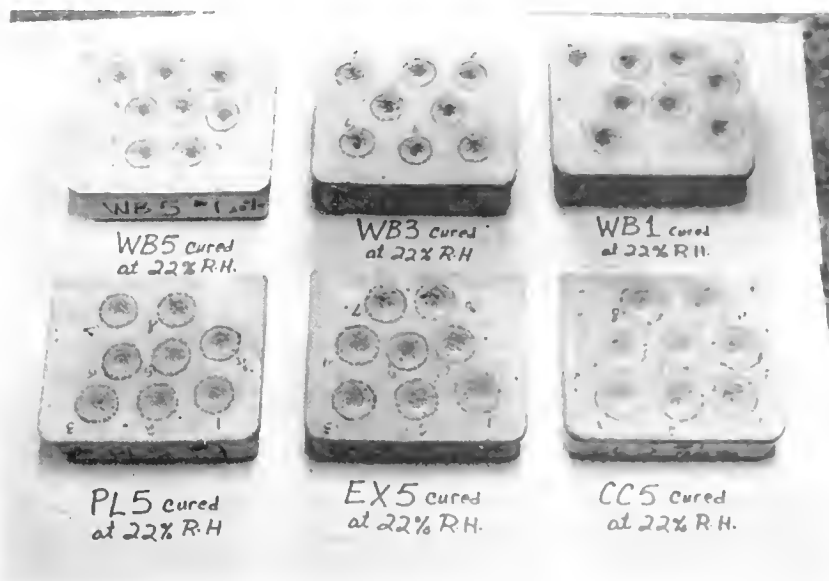


FIG. 8 SANDBLASTED ABRASION TEST SAMPLES.



FIG. 9 VOLUME DETERMINATION OF ABRADED CAVITIES.

STATISTICAL DESIGN OF EXPERIMENTS

Introduction

The sample preparation phase of this research project was subjected to a troublesome time constraint that necessitated the preparation of the mortar slabs in only three weeks. The design of the experiment was, therefore, heavily influenced by this overriding factor. For example, the maximum curing duration had to be cut from the original plan of seven days to five days, and the maximum number of slabs made was based on the time that was available to make them. By the time the three most important factors in the study were accounted for, there was no time left to prepare more samples for repeating the experimentation in order to have a proper error term and a wider inference space. As it is, unless it is stated otherwise, the conclusions from this study are applicable only to one set of observations, owing to lack of replication. Although the time constraint resulted in a design that did not lend itself to a better statistical analysis, it introduced an interesting and worthwhile problem concerning the preservation of the samples until they were tested. A considerable amount of time was spent in determining a method by which the mass-produced samples could be preserved in their original conditions by preventing

further hydration until they were tested, but without altering them to any significant degree.

Choice of Factors and Levels

This study was initially conceived to involve mixes with different mix proportions and samples with different surface finishes. It was later thought to keep these two factors constant for the sake of simplicity and to adhere to the tight sample preparation schedule, but samples with two different types of sand having the same mix proportions and surface finishes were made. "Type of sand" is not treated as a factor because although the mixes with the two types of sand had the same mix proportions, as it was proved later, they were thought to contain different air contents and air systems, owing to variations in the particle size and gradation of the two sands. Hence, instead of including types of sand as a factor, two experiments one with regular and the other with silica-sand were run.

Eventually, the following three factors were included in the study:

1. Method of curing, with four levels.
2. Atmospheric conditions, with six levels.
3. Duration of curing, with three levels.

The four levels for method of curing included: curing with wet burlap (WB), with plastic cover (PL), with curing compound (CC), and with no cover (EX), and for all four methods of curing the duration of curing was five days. The six

different atmospheric conditions were produced by, each time, setting the relative humidity of the curing chamber to 22%, 44% and 72%, and having an area with and without wind for each relative humidity condition. To study the effect of atmospheric conditions, all the samples were cured with no cover. The three levels for duration of curing were, one day, three days, and five days, and the curing method for all three durations involved the use of wet burlap.

Method of curing and atmospheric conditions are both qualitative factors, and their levels were fixed. On the other hand, duration of curing is a quantitative factor with fixed levels. Due to the fixed nature of all the factor levels, the conclusions in this study pertain to just those factor levels.

There were also three response or dependent variables, namely, absorptivity, non-evaporable water content, and abrasion loss. The absorptivity tests and non-evaporable water determinations were done on various layers of cores taken from each sample, and, therefore, a "depth" factor was included. At each depth, and for each treatment combination, two observations were made. The two observations are given the designation "cores", and they are nested within each treatment combination involving method of curing and humidity, atmospheric conditions, or duration of curing and humidity, as the case may be. The cores are considered random. In the case of the dependent variable, abrasion loss, all the

observations were from tests done on the surface only, and there was no depth factor involved. For each treatment combination eight observations were made, and again the observations are nested within the various treatment combinations.

Randomization

As it was explained in greater detail in the sample preparation section, for each relative humidity condition in the chamber, three batches of mortar were made with regular sand and three more with silica sand for two experiments. The humidity conditions in the chamber were not set randomly, because it was easier for the air conditioning equipment to operate from a low to a higher humidity rather than from high to low. Therefore, for the first week of sample preparation the relative humidity was set at 22%, for the second week at 44% and for the third week at 72%. Hence, there is complete confounding of order and time with the effect of relative humidity.

From each group of the three batches made with regular sand, during each of the three relative humidity conditions, two sets of seven slabs were made. The first set of slabs were tested and/or preserved in methanol soon after the end of their respective curing periods, and the second set were kept under cycles of wetting and drying for three months before they were tested. After casting each set of seven slabs, a random procedure was used to decide which slab was

to be subjected to what curing condition and duration. Table 7 shows which slab was cast from which batch, for the first set of seven slabs at each of the three relative humidity conditions.

Table 7. Identification of Batches from which Individual Slabs were Made*

Sample**	Batch Number		
	@ 22% R.H.	@ 44% R.H.	@ 72% R.H.
WB1	A-3	A-4	A-7
WB3	A-2	A-6	A-8
WB5	A-2	A-5	A-7
PL5	A-1	A-4	A-7
CC5	A-2	A-5	A-8
EX5	A-1	A-4	A-9
EW5	A-1	A-6	A-9

*For the first set of slabs which were tested soon after termination of curing.

**Note: The alphanumeric characters represent method of curing and duration of curing. The numbers 1, 3 and 5 stand for duration of curing in days, and the letters should be interpreted as follows: WB for wet burlap, PL for plastic cover, CC for curing compound, EX for exposed and EW for exposed in a windy condition.

The three batches made of silica sand were combined before the slabs were cast, therefore there was no randomization involved in connection with batches.

Layouts for the Experimentation

The experimental layouts for the three factors in question are illustrated in Tables 8-13. They are applicable

for both regular and silica sand samples. As shown on the tables, the three factors in the study were analyzed separately. Two of the three response variables, absorptivity and non-evaporable water content, have the same layouts involving depth, but for the third dependent variable, the layouts are different due to the absence of the depth factor. As shown in Table 8, the analysis for the factor, method of curing, involves a nested three factor factorial experiment where three humidities and six depths were used for each method of curing and the cores are nested within method and humidity. Note that there is only one slab per method. A similar arrangement is also seen in Table 10 for duration of curing. On the other hand, Table 9 shows a layout that indicates a nested two factor factorial experiment for the analysis of the effect of atmospheric conditions on the dependent variables, absorptivity and non-evaporable water content. Again, in this case the cores are nested within each atmospheric condition.

The layouts and models for the third dependent variable, abrasion loss, are presented in Tables 11-13.

Statistical Models

One approach to analyze the data from a well designed experiment is to show the model appropriate to describe the association of the effects of the factors in the experiment with the responses of interest. This association must include the effect of the procedure in acquiring the data,

including the randomization, and replication methods. Anderson and McLean (43) describe, in detail, techniques for handling this problem and show analysis of variance (ANOVA) tables that correspond to various models.

The models for Tables 8-13 are given below, and the numbers above each of the terms represent the degrees of freedom for that term.

The model representing Table 8 is:

$$\begin{aligned}
 144 = 1 + 3 + 2 + 6 + 12 + 0 + 5 + 15 \\
 Y_{ijkl} = \mu + M_i + H_j + MH_{ij} + C_{(ij)k} + \delta_{(ijk)} + D_l + MD_{il} \\
 + 10 + 30 + 60 \\
 + HD_{jl} + MHD_{ijl} + CD_{(ij)kl}
 \end{aligned}
 \tag{2}$$

$$i = 1, 2, 3, 4 \quad j = 1, 2, 3 \quad k = 1, 2 \quad l = 1, 2, \dots, 6$$

where

Y_{ijkl} = absorptivity or non-evaporable water content of the k^{th} core for the i^{th} method of curing, the j^{th} relative humidity, and the l^{th} depth

μ = overall mean

M_i = the effect of the i^{th} method of curing (fixed)

H_j = the effect of the j^{th} relative humidity (fixed)

MH_{ij} = the effect of the interaction of the i^{th} method of curing and the j^{th} relative humidity

$C_{(ij)k}$ = the effect of k^{th} core (random) in the i^{th} method of curing and the j^{th} relative humidity

$\delta_{(ijk)}$ = restriction error (random) caused by the 6 depths being run in the k^{th} core of the i^{th} method of

curing. This term has zero degrees of freedom and no sum of squares. It appears in the model to distinguish this nested design from a completely randomized design, and indicate that the 6 depths occur at each core.

D_1 = the effect of the 1th depth (fixed)

MD_{il} = the effect of the interaction of the ith method of curing with the jth depth

HD_{jl} = the effect of the interaction of the jth relative humidity with the 1th depth

MHD_{ijl} = interaction effect of the ith method of curing with the jth relative humidity and the 1th depth

$CD_{(ij)kl}$ = interaction effect of the kth core within the ith method of curing and the jth relative humidity, and the 1th depth

The model for Table 9 is:

$$\begin{aligned}
 72 &= 1 + 5 + 6 + 0 + 5 + 25 + 30 \\
 Y_{ijk} &= \mu + A_i + C_{(i)j} + \delta_{(ij)} + D_k + AD_{ik} + CD_{(i)jk} \\
 i &= 1, 2, \dots, 6 \\
 j &= 1, 2 \\
 k &= 1, 2, \dots, 6
 \end{aligned}
 \tag{3}$$

and each term can be interpreted in the same way as the terms in the previous model.

The model for Table 10 is:

$$\begin{aligned}
 108 &= 1 + 2 + 2 + 4 + 9 + 0 + 5 + 10 \\
 Y_{ijkl} &= \mu + T_i + H_j + TH_{ij} + C_{(ij)k} + \delta_{(ijk)} + D_l + TD_{il} \\
 &\quad + 10 + 20 + 45 \\
 &\quad + HD_{jl} + THD_{ijl} + CD_{(ij)kl} \\
 i &= 1, 2, 3 \qquad k = 1, 2 \\
 j &= 1, 2, 3 \qquad l = 1, 2, \dots, 6
 \end{aligned} \tag{4}$$

The model for Table 11 is:

$$\begin{aligned}
 96 &= 1 + 3 + 2 + 6 + 84 + 0 \\
 Y_{ijk} &= \mu + M_i + H_j + MH_{ij} + O_{(ij)k} + \delta_{(ijk)} \\
 i &= 1, 2, 3, 4 \qquad k = 1, 2, \dots, 8 \\
 j &= 1, 2, 3
 \end{aligned} \tag{5}$$

The model that represents Table 12 is:

$$\begin{aligned}
 48 &= 1 + 5 + 42 + 0 \\
 Y_{ij} &= \mu + A_i + O_{(i)j} + \delta_{(ij)} \\
 i &= 1, 2, \dots, 6 \qquad j = 1, 2, \dots, 8
 \end{aligned} \tag{6}$$

And finally, the model for Table 13 is:

$$\begin{aligned}
 72 &= 1 + 2 + 2 + 4 + 63 + 0 \\
 Y_{ijk} &= \mu + T_i + H_j + TH_{ij} + O_{(ij)k} + \delta_{(ijk)} \\
 i &= 1, 2, 3 \qquad k = 1, 2, \dots, 8 \\
 j &= 1, 2, 3
 \end{aligned} \tag{7}$$

Table 8. Experimental Layout for the Dependent Variables Absorptivity and Non-evaporable Water Content, and the Independent Variable Method of Curing

Depth (D)	Method (M)											
	1			2			3			4		
	Humidity (H)			Humidity			Humidity			Humidity		
	1	2	3	1	2	3	1	2	3	1	2	3
	Core (C)	C	C	C	C	C	C	C	C	C	C	C
	1	2	. . .								23	24
1 cm							1					
2							2					
3							.					
4							.					
5							.					
6							6					

Method:

1 = Wet burlap (WB)
 2 = Plastic cover (PL)
 3 = Curing compound (CC)
 4 = Exposed (EX)

Humidity:

1 = 22%
 2 = 44%
 3 = 72%

Table 9. Experimental Layout for the Dependent Variables Absorptivity and Non-evaporable Water Content, and the Independent Variable Atmospheric Conditions

Depth (D)	Atmospheric Conditions (A)											
	1		2		3		4		5		6	
	Core (C)		Core		Core		Core		Core		Core	
	1	2	3	4	5	6	7	8	9	10	11	12
1 cm					1				1			
2					2				2			
3					.				.			
4					.				.			
5					.				.			
6					6				6			

Atmospheric conditions:

- 1 = 22% R.H. with wind
- 2 = 44% " " "
- 3 = 72% " " "
- 4 = 22% " without wind
- 5 = 44% " " "
- 6 = 72% " " "

Table 10. Experimental Layout for the Dependent Variables Absorptivity and Non-evaporable Water Content, and the Independent Variable Duration of Curing

Depth (D)	Duration (T)											
	1			2			3			Humidity		
	Humidity (H)			Humidity			Humidity			Humidity		
	1	2	3	1	2	3	1	2	3	1	2	3
Core(C)	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core
1	3	4	5	6	7	8	9	10	11	12	13	14
2	1	2	3	4	5	6	7	8	9	10	11	12
3	1	2	3	4	5	6	7	8	9	10	11	12
4	1	2	3	4	5	6	7	8	9	10	11	12
5	1	2	3	4	5	6	7	8	9	10	11	12
6	1	2	3	4	5	6	7	8	9	10	11	12

Humidity:

1 = 22%
2 = 44%
3 = 72%

Duration:

1 = 1 day
2 = 3 days
3 = 5 days

Table 11. Experimental Layout for the Dependent Variable
Abrasion Loss, and the Independent Variable
Method of Curing

Observations (O)	Method (M)											
	1			2			3			4		
	Humidity (H)			Humidity			Humidity			Humidity		
	1	2	3	1	2	3	1	2	3	1	2	3
1							1					
2							2					
.							.					
.							.					
.							.					
8							8					

Method:

1 = Wet burlap (WB)
 2 = Plastic cover (PL)
 3 = Curing Compound (CC)
 4 = Exposed (EX)

Humidity:

1 = 22%
 2 = 44%
 3 = 72%

Table 12. Experimental Layout for the Dependent Variable Abrasion Loss, and the Independent Variable Atmospheric Conditions

Observations (O)	Atmospheric Conditions (A)					
	1	2	3	4	5	6
1			1			1
2			2			2
.			.			.
.			.			.
.			.			.
8			8			8

Atmospheric Conditions:

1 = 22% R.H. with wind
 2 = 44% " " "
 3 = 72% " " "
 4 = 22% " without wind
 5 = 44% " " "
 6 = 72% " " "

Table 13. Experimental Layout for the Dependent Variable Abrasion Loss, and the Independent Variable Duration of Curing

Observations (O)	Duration (T)								
	1			2			3		
	Humidity			Humidity			Humidity		
	1	2	3	1	2	3	1	2	3
1				1			1		
2				2			2		
.				.			.		
.				.			.		
.				.			.		
8				8			8		

Duration:

1 = 1 day
 2 = 3 days
 3 = 5 days

Humidity:

1 = 22%
 2 = 44%
 3 = 72%

Statistical Analysis

In keeping with the objectives of this study, the data produced by the three test methods were analyzed in order to answer the following questions.

1. Were the three test methods or response variables sensitive enough to detect differences in the various mortar samples that were cured under different curing conditions and durations?

2. Are there relationships between absorptivity, non-evaporable water content, and abrasion resistance of the mortar samples?

3. What were the effects of the initial curing conditions and duration on the properties of the mortar samples three months later?

4. Is it possible to give a range of some function of absorptivity and/or non-evaporable water content values with a certain confidence coefficient to distinguish between adequate and inadequate curing?

To answer these questions, the data were grouped, for the most part, according to the layouts shown in Tables 8-13, and a number of analyses of variance were carried out. Special attention was paid to the interaction terms, and where interactions proved to be significant, further one-way analyses of variance were done, and plots were made to graphically show some of the interesting responses which were thought to contribute to the understanding of the problem.

Once the significant effects of the factors of the response variables were identified, further analyses were done to find out the differences between the various factor level means by using the Newman-Keuls test which allows investigation of all possible pairs of means. To determine the relationships between non-evaporable water, absorptivity, and abrasion resistance, the least squares method was used. All the analyses were done using canned programs from the Purdue University Computing Center library.

The data for both regular and silica sand samples were analyzed, but in the case of the samples that were tested at age three months, after enduring cycles of wetting and drying, only the data from the regular sand samples were used.

Unless it is stated otherwise, all the hypothesis tests are at $\alpha = 0.05$ level.

RESULTS AND DISCUSSION

Introduction

In the following sections the data from the three response variables will be presented along with the analyses of the data. The data from the absorptivity tests consist of results of tests done at eight different layers of each sample. However, for the analyses, only the data from depths 1 cm to 6 cm were used. The absorptivity for the top 1 cm of each core was disregarded because the value for the very top region of each core was affected not only by the curing but also by what was thought to be the formation of water channels from bleeding. Even samples that were cured immersed in lime water starting at final set exhibited high absorptivity values in their very top regions. The data from the bottom 1 cm of the samples were also not used because as will be shown later, the effect of curing was minimal at that level. For the analyses of the non-evaporable water test results, only the data from the top 6 cm of each sample were used. There are two reasons for not using the data for the bottom 2 cm; first, as stated earlier, the effect of curing is negligible at those depths, and secondly, as will be shown on graphs in subsequent sections, the non-evaporable water contents for the bottom 2 cm of almost all the samples

were unexpectedly low. Although the reason for the drop is not clear, there is one possible explanation. In his paper on the bleeding of concrete, Powers (44) indicated that a highway slab, for example, will have at the end of the bleeding period a zone of maximum compaction with the lowest water content at the bottom, a transition zone of variable water content above it, and near the top surface, a third zone with constant water content. If the water content was too low at the bottom of the samples it may have caused a drop in the non-evaporable water content without affecting the absorptivity, since low water-to-cement ratio causes a reduction in pore sizes that results in low absorptivity. Note that for mixes with two different water-to-cement ratios it is possible to have the same non-evaporable water content, but the absorptivity values will be different.

For the samples that were tested three months after the end of their respective initial curing periods, no data are presented involving non-evaporable water determinations, and the data, as well as the analyses regarding the absorptivity tests, will be for regular sand samples cured at 22% and 44% relative humidity (R.H.) conditions only. However, the abrasion test results are for all three R.H. conditions.

Absorptivity Test

In Tables 14-17 the results of the calculations of absorptivity of both regular and silica sand samples cured under different conditions and durations are presented.

Table 14. Absorbivity Test Results for Samples Made of Regular Sand and Cured Under Different Conditions for 5 Days

Relative Humidity	Curing Condition	K_a ($\times 10^{-6}$ cm ² /sec)*							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
22%	WB	7.28	2.09	1.54	1.32	1.32	1.12	1.15	1.09
	PL	5.52	1.73	1.63	1.26	1.26	1.15	0.99	0.94
	CC	40.30	14.50	6.73	4.06	3.17	1.73	1.15	1.04
	EX	26.27	10.70	5.64	3.90	3.13	2.86	2.86	1.70
	EW	14.90	7.21	4.93	4.11	3.17	2.36	2.02	1.32
44%	WB	8.51	1.35	1.01	1.04	0.86	0.70	0.75	0.58
	PL	6.08	2.09	1.63	1.63	1.67	1.12	1.07	0.68
	CC	19.83	11.62	3.17	1.32	1.44	1.20	1.04	0.68
	EX	40.00	10.25	3.85	2.16	2.16	1.60	1.12	0.94
	EW	9.52	6.73	2.24	2.36	2.01	2.01	1.57	1.20
72%	WB	5.89	1.12	0.91	0.99	0.98	0.91	0.77	0.50
	PL	10.33	2.90	1.54	1.54	1.35	0.96	0.84	0.54
	CC	21.70	8.29	2.65	2.20	1.70	1.35	1.44	0.96
	EX	29.96	8.00	2.56	2.20	1.30	1.32	1.07	0.75
	EW	28.70	8.29	3.60	2.90	1.84	1.73	1.84	0.96

*Average of two observations

Table 15. Absorbitivity Test Results for Samples Made of Regular Sand and Cured with Wet Burlap for Different Lengths of Time and at Different Relative Humidities

Relative Humidity	Curing Duration (Days)	$K_a \text{ (} \times 10^{-6} \text{ cm}^2/\text{sec})^*$							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
22%	1	23.40	16.00	12.70	11.40	9.60	10.00	9.36	8.82
	3	12.60	3.90	2.86	2.32	1.63	1.87	1.80	
	5	7.28	2.09	1.54	1.32	1.32	1.12	1.15	1.09
44%	1	36.80	16.10	17.10	13.80	11.60	9.60	8.00	7.56
	3	11.90	4.93	4.82	3.65	3.36	3.31	2.86	2.40
	5	8.51	1.35	1.01	1.04	0.86	0.70	0.75	0.58
72%	1	24.45	5.83	4.06	3.31	2.86	2.28	1.91	1.91
	3	7.56	1.35	1.04	0.99	0.94	0.79	1.01	0.77
	5	5.89	1.12	0.91	0.99	0.98	0.91	0.77	0.50

*Average of two observations

Table 16. Absorbitivity Test Results for Samples Made of Silica Sand and Cured Under Different Conditions for 5 Days

Relative Humidity	Curing Condition	$K_a \text{ (x } 10^{-6} \text{ cm}^2/\text{sec})^*$							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
22%	WB	3.36	1.54	1.60	1.47	1.50	1.15	1.07	
	PL	4.37	2.48	2.32	1.98	1.23	1.15	1.18	0.82
	CC	34.20	15.30	6.34	5.34	3.22	1.67	1.23	1.07
	EX	28.40	12.80	8.89	7.07	4.00	2.69	2.09	
	EW	7.70	3.65	2.73	2.90	2.86	2.48	2.28	2.02
44%	WB	6.73	0.99	1.04	0.68	0.75	0.54	0.45	0.38
	PL	4.70	1.87	1.38	1.73	1.14	0.90	0.58	0.50
	CC	29.50	15.71	4.37	2.40	1.67	1.38	1.18	1.07
	EX	28.60	10.90	4.06	3.04	3.80	5.16	3.80	1.56
	EW	7.07	4.06	3.13	3.31	2.48	1.87	1.80	1.57
72%	WB	6.53	1.07	0.84	0.86	1.12	0.91	0.82	0.54
	PL	4.87	2.68	2.05	1.41	1.14	0.89	0.82	0.54
	CC	15.10	8.07	3.70	3.00	2.82	2.65	1.60	0.91
	EX	16.64	7.00	4.00	3.31	2.90	1.87	0.94	0.66
	EW	21.80	6.80	5.28	4.99	4.43	3.60	1.87	0.86

*Average of two observations

Table 17. Absorbivity Test Results for Samples Made of Silica Sand and Cured with Wet Burlap for Different Lengths of Time and at Different Relative Humidities

Relative Humidity	Curing Duration (Days)	$K_a \text{ (x } 10^{-6} \text{ cm}^2/\text{sec)}^*$							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
22%	1	11.89	10.10	7.35	8.29	6.80	5.83	4.87	3.47
	3	16.43	6.40	4.48	4.00	4.65	3.36	3.50	3.00
	5	3.36	1.54	1.60	1.47	1.50	1.15	1.07	
44%	1	19.72	13.35	13.10	11.30	12.20	10.80	11.00	6.02
	3	9.44	1.01	0.82	0.91	0.96	1.09	0.66	0.50
	5	6.73	0.99	1.04	0.68	0.75	0.54	0.45	0.38
72%	1	28.30	6.34	4.32	3.95	4.11	4.32	2.82	1.73
	3	10.25	1.76	1.20	1.35	1.23	1.20	0.94	0.75
	5	6.53	1.07	0.84	0.86	1.12	0.91	0.82	0.54

*Average of two observations

The absorptivity, K_a , was calculated using Equation 1 on pg. 36.

Effect of Method of Curing

To determine the sensitivity of the absorptivity test to variations in cement paste properties, as affected by the four curing methods at the three R.H. conditions, and at the six depths, an analysis of variance was run according to the layout in Table 8, and in keeping with the model in Equation 2. This analysis, presented in the appendix, was designated ANOVA 1.

ANOVA 1 shows that, in addition to the three main effects, method of curing (M), relative humidity (H), and depth (D), all three 2-factor interactions, and the 3-factor interaction, were all significant at the $\alpha = 0.05$ level. The changes in absorptivity with depth for the four methods of curing at each of the three R.H. conditions are shown in Figures 10-12. Note that in each figure there is a fifth curve labeled EW5. Although this condition was not treated as one of the methods of curing in the analysis, it was included to show the interesting response, in relation to the others, of the samples that were allowed to dry in a windy environment throughout their curing periods.

As shown by the significance of the interaction of M by H in ANOVA 1, the effect of method of curing on absorptivity was different from one relative humidity condition to another. Therefore ANOVA 1A (shown in the appendix) was run to examine the effect of method of curing at each of the three

R.H. conditions based on absorptivity at a depth of 1 cm. This analysis revealed that at 22% and 44% R.H. conditions there was a significant difference in absorptivity for the four methods of curing, but at 72% R.H. condition the four methods of curing did not produce significantly different results at $\alpha = 0.05$ level, but they were significant at $\alpha = 0.10$ level. This can be seen in Figures 10-12 by how far apart the data points are at a depth of 1 cm. The data points are the farthest apart at 22% R.H. and the closest at 72% R.H. In Figures 13-16, the responses for each of the four methods of curing at the three R.H. conditions are illustrated. Thus, ANOVA 1A illustrates the fact that the absorptivity test was sensitive enough to show the consequences of the quality of the curing methods in relation to the severity of the curing environments. To find out the differences in the absorptivity values at a depth of 1 cm among the four methods of curing for the 22% and 44% R.H. conditions, a Newman-Keuls test, referred to in the appendix as N-K 1A, was run. The analysis demonstrates that at 22% R.H. condition, curing with wet burlap and with a plastic cover did result in essentially the same absorptivity values, and the other two curing methods produced significantly different values. This is also illustrated in Figure 10. At 44% R.H. condition, the samples cured with wet burlap and with plastic cover, again, had the same absorptivity values, and the other two, cured with curing compound and with no

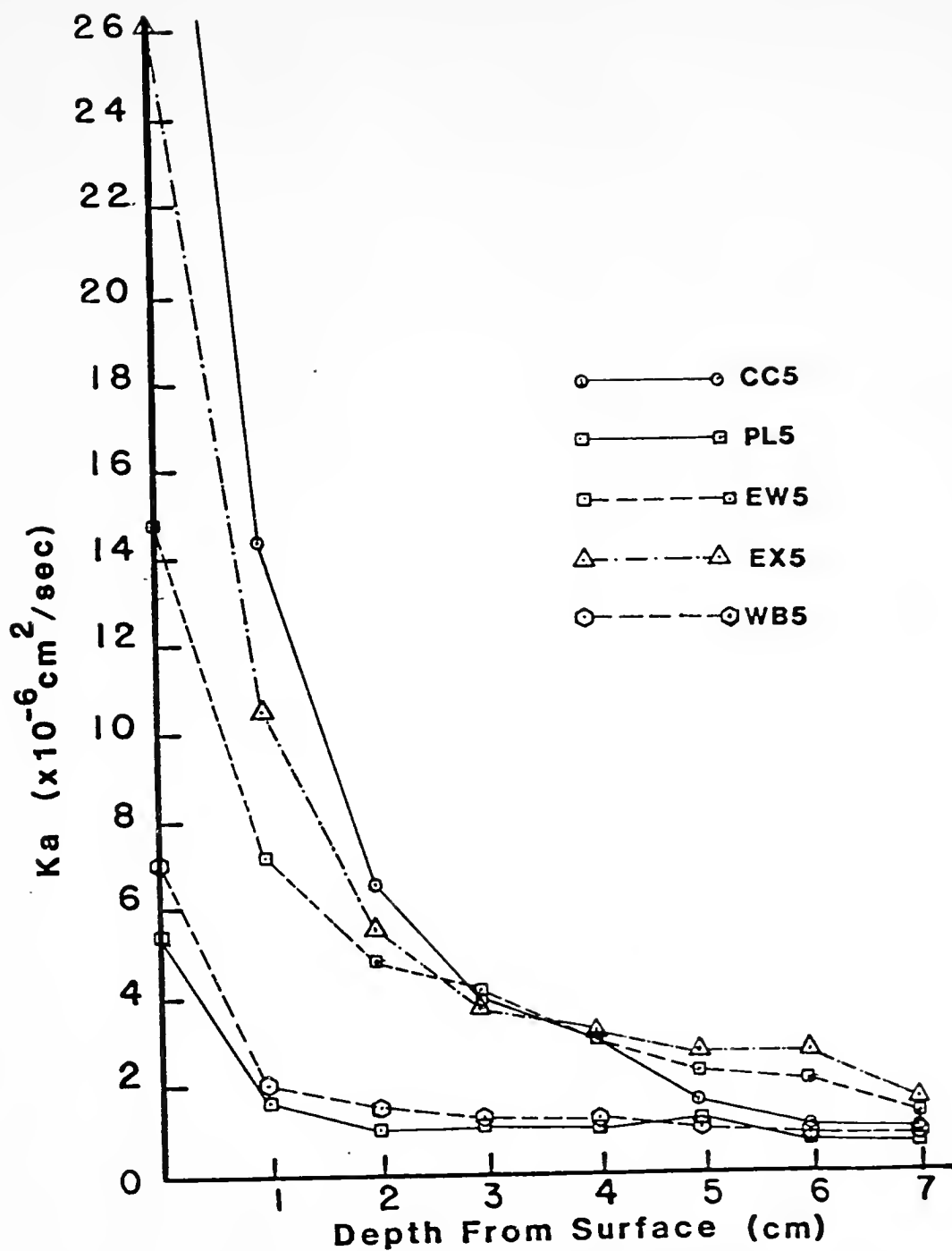


FIG. 10 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED AT 22% R.H. FOR 5 DAYS.

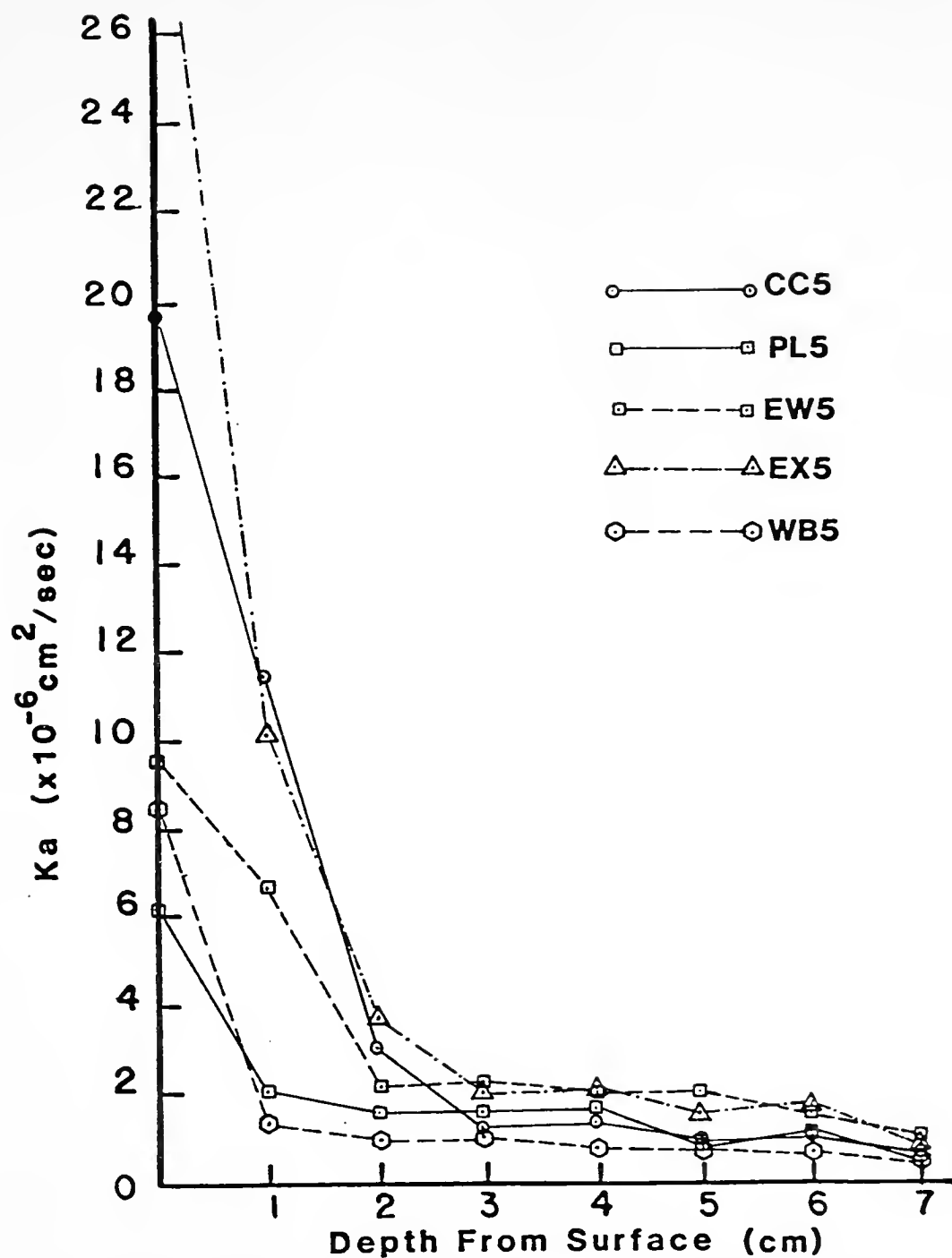


FIG. 11 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED AT 44% R.H. FOR 5 DAYS.

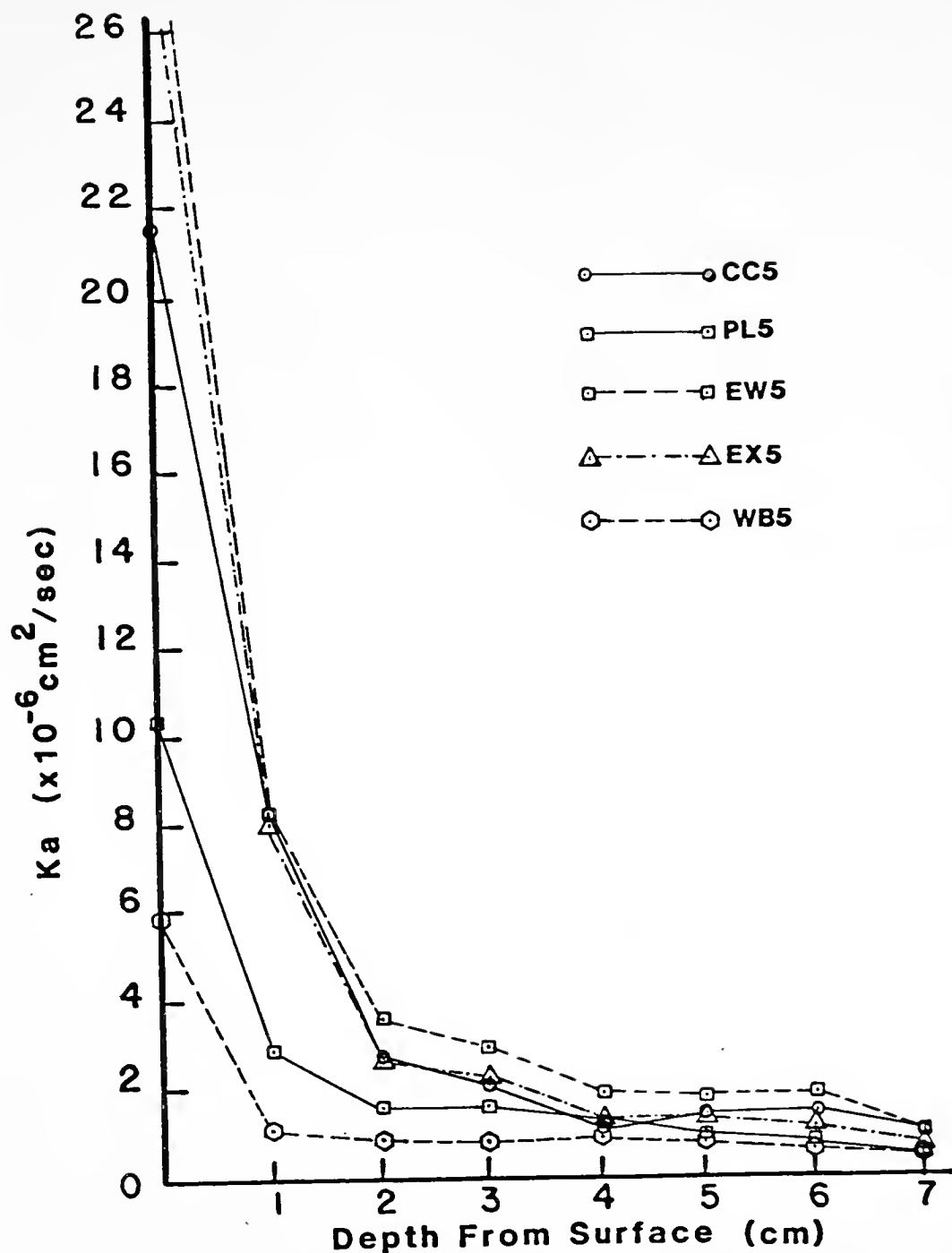


FIG. 12 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED AT 72% R.H. FOR 5 DAYS.

cover, produced the same result although significantly different from the first two. This can be seen in Figure 11.

To evaluate the interaction of method of curing by depth, from ANOVA 1, in other words, to examine how the change in absorptivity with depth varied for the four methods of curing, ANOVA 1B was run for the three R.H. conditions. The result indicates that at all three R.H. conditions there were no significant changes in absorptivity with depth for the samples cured with wet burlap and with plastic cover, but the changes in absorptivity with depth were significantly different for the samples cured with the curing compound and with no cover. Note that according to the analyses in ANOVA 1B, for the 44% and 72% R.H. conditions, significant changes in absorptivity with depth were indicated for the PL5 sample at 44% R.H. and for the WB5 at 72% R.H. But as can be seen in Figures 11 and 12, the changes were restricted to the top 1 cm or so, and for all practical purposes they can be neglected. Comparison of Figures 10-12 shows that the changes in absorptivity with depth for all four methods of curing decreased with the increase in relative humidity of the curing environment. To compare the absorptivity values at the six depths for the two samples that displayed significant change with depth, i.e., for CC5 and EX5 at 22% R.H., Newman-Keuls analysis, referred to as N-K 1B, was run. For CC5, the values for the top 3 cm were significantly different from each other, and below 3 cm there was similarity

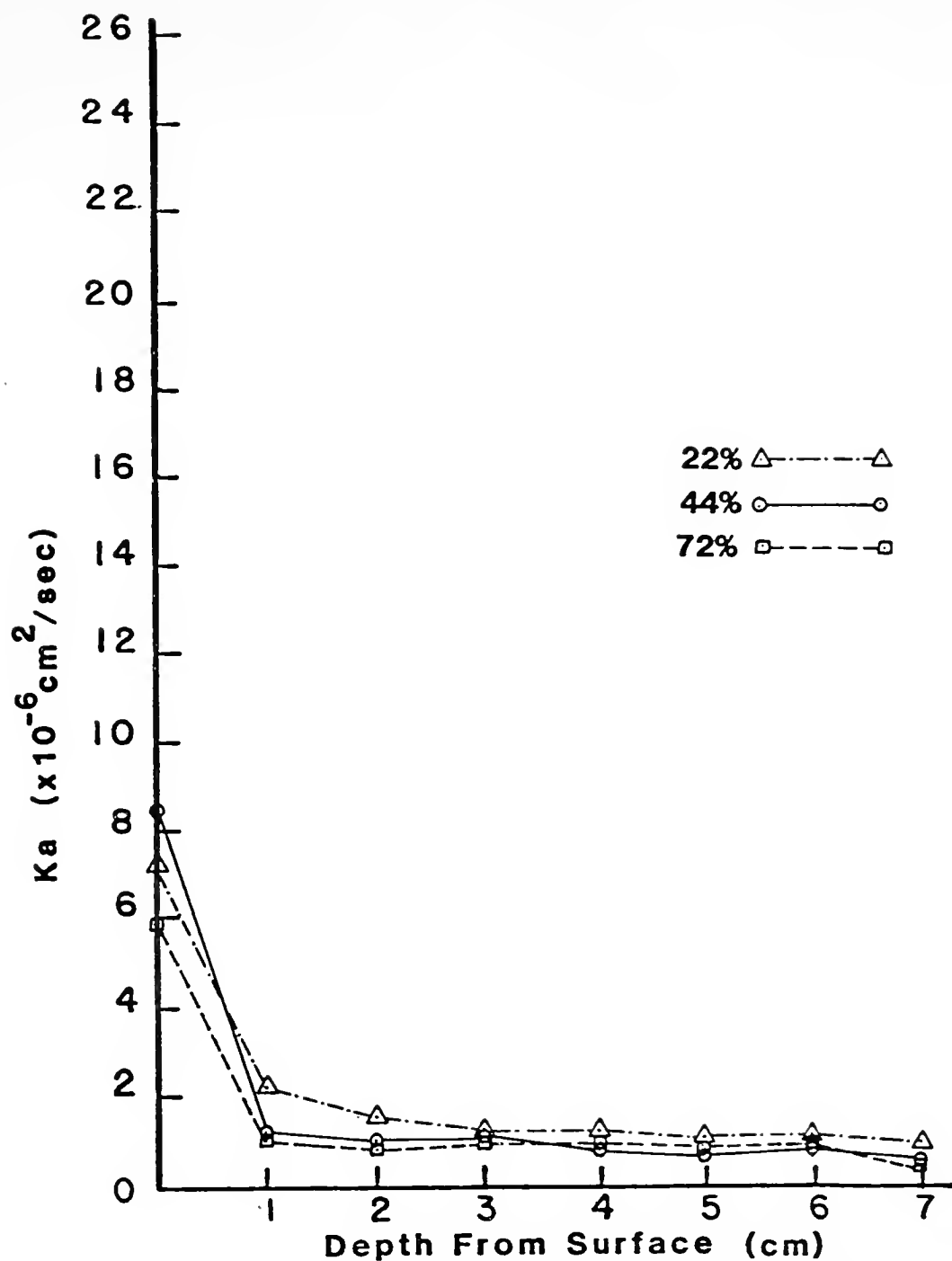


FIG. 13 ABSORPTIVITY TEST RESULTS FOR WB5 SAMPLES MADE OF REGULAR SAND AND CURED AT THE 3 RELATIVE HUMIDITY CONDITIONS.

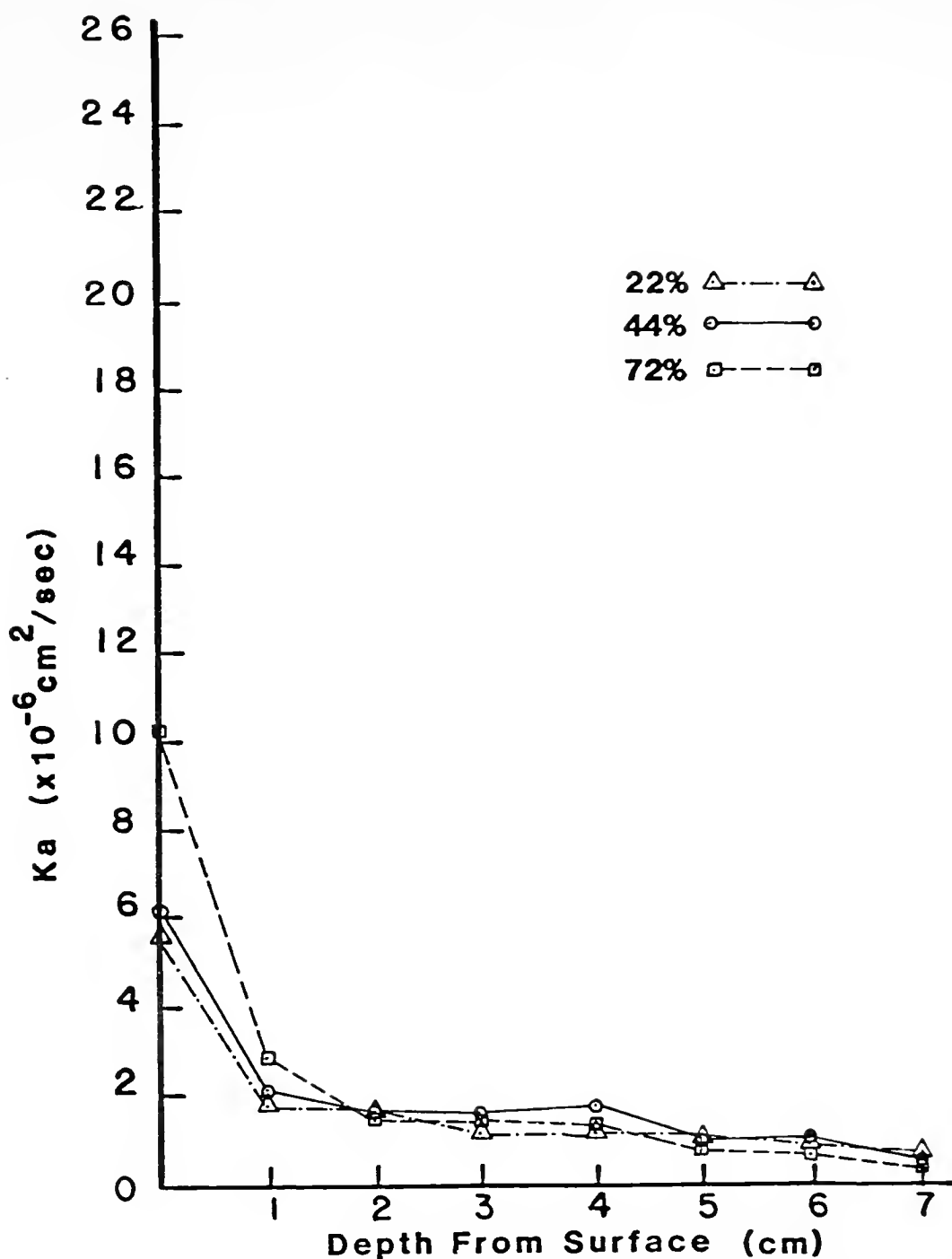


FIG. 14 ABSORPTIVITY TEST RESULTS FOR PL5 SAMPLES MADE OF REGULAR SAND AND CURED AT THE 3 RELATIVE HUMIDITY CONDITIONS.

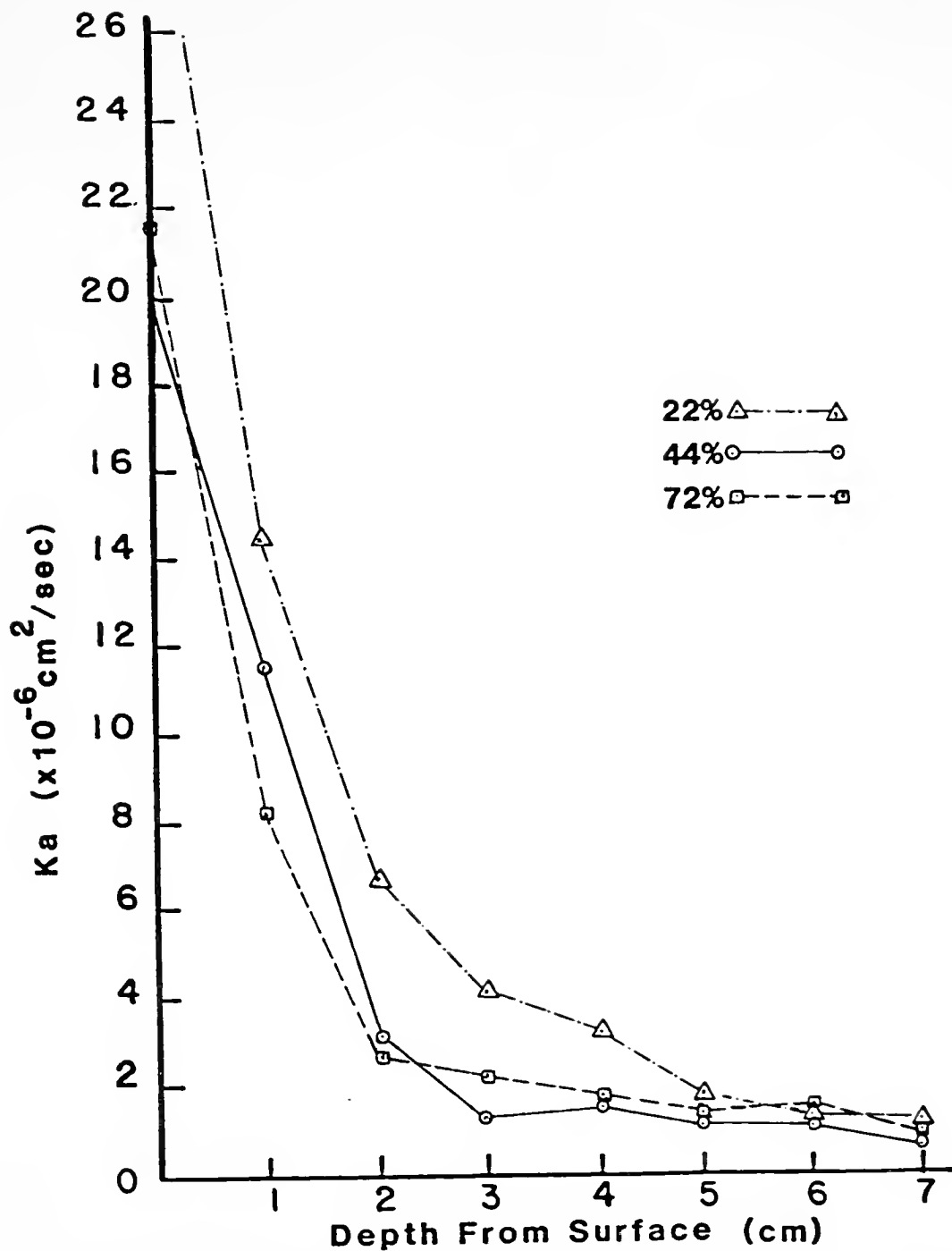


FIG. 15 ABSORPTIVITY TEST RESULTS FOR CC5 SAMPLES MADE OF REGULAR SAND AND CURED AT THE 3 RELATIVE HUMIDITY CONDITIONS.

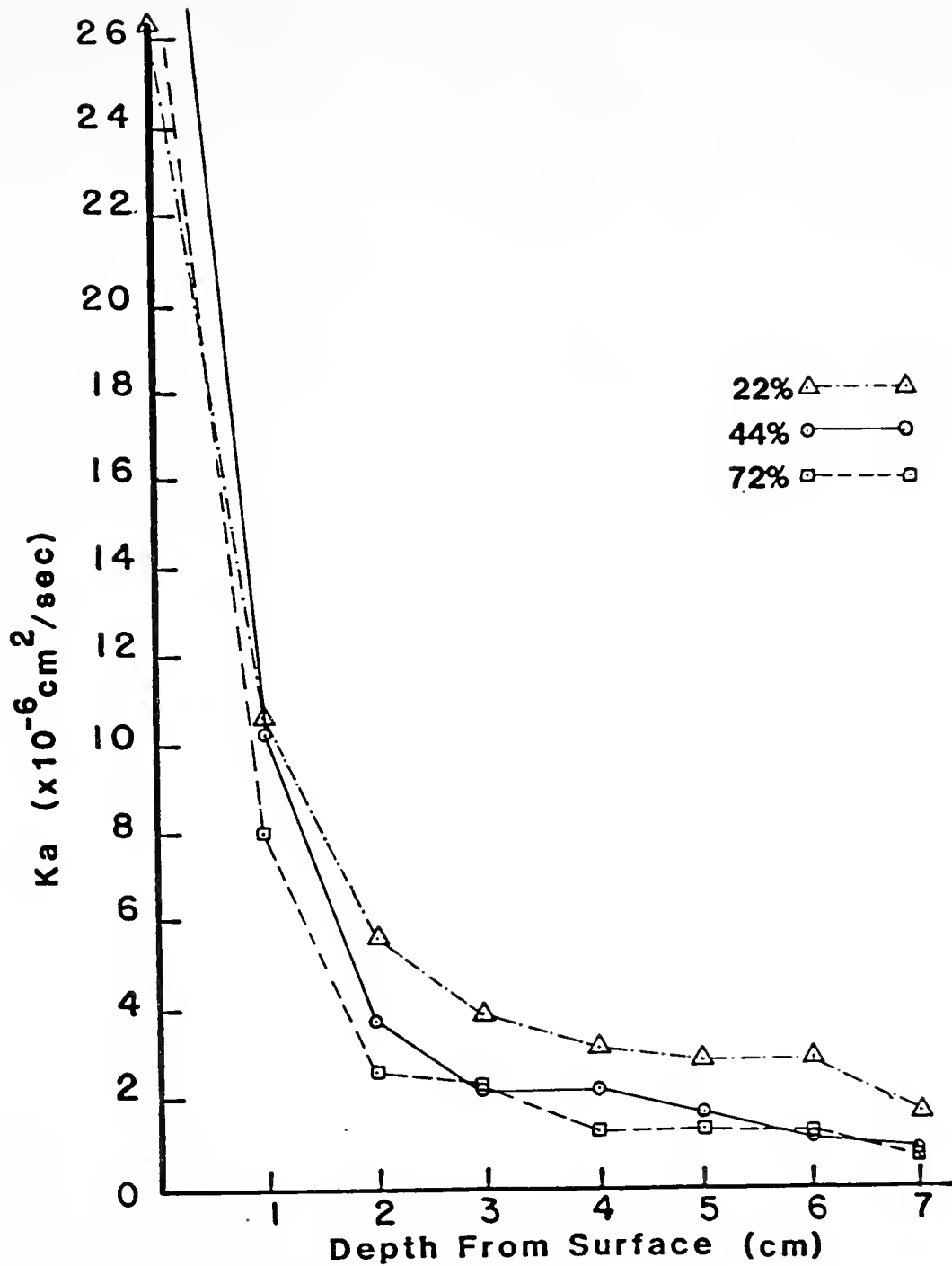


FIG. 16 ABSORPTIVITY TEST RESULTS FOR EX5 SAMPLES MADE OF REGULAR SAND AND CURED AT THE 3 RELATIVE HUMIDITY CONDITIONS.

among the consecutive layers. For EX5, again, the significant differences between the consecutive layers were mostly in the top 3 cm. Thus, as will be shown again, the effect of poor curing seemed to affect approximately the top 3 cm of the slabs, and the affected zone decreased with the quality of the curing.

It is interesting to note the position of the curves for the EW5 samples in Figures 10-13. That condition of curing was not as good as curing with wet burlap or with plastic cover, but it was not as bad as the exposed condition without wind, or the curing with what turned out to be an ineffective curing compound. The explanation, as stated in the literature review section, is that rapid evaporation of water before a concrete mixture reaches initial set has a tendency to densify the surface, as a result of forces due to capillary action and surface tension. There is also a belief that the effective water-cement ratio at the surface is reduced by evaporation that takes place before initial set, which means an increase in strength.

Similar series of analyses were done on the data obtained from the samples made with silica sand. The analyses are not shown, but tabulated absorptivity values (Tables 16 and 17) and plots as seen in Figures 17-19 are presented. The results are similar to those from regular sand samples. Comparison of the corresponding figures indicates that the trends are alike. One difference between the two sets of

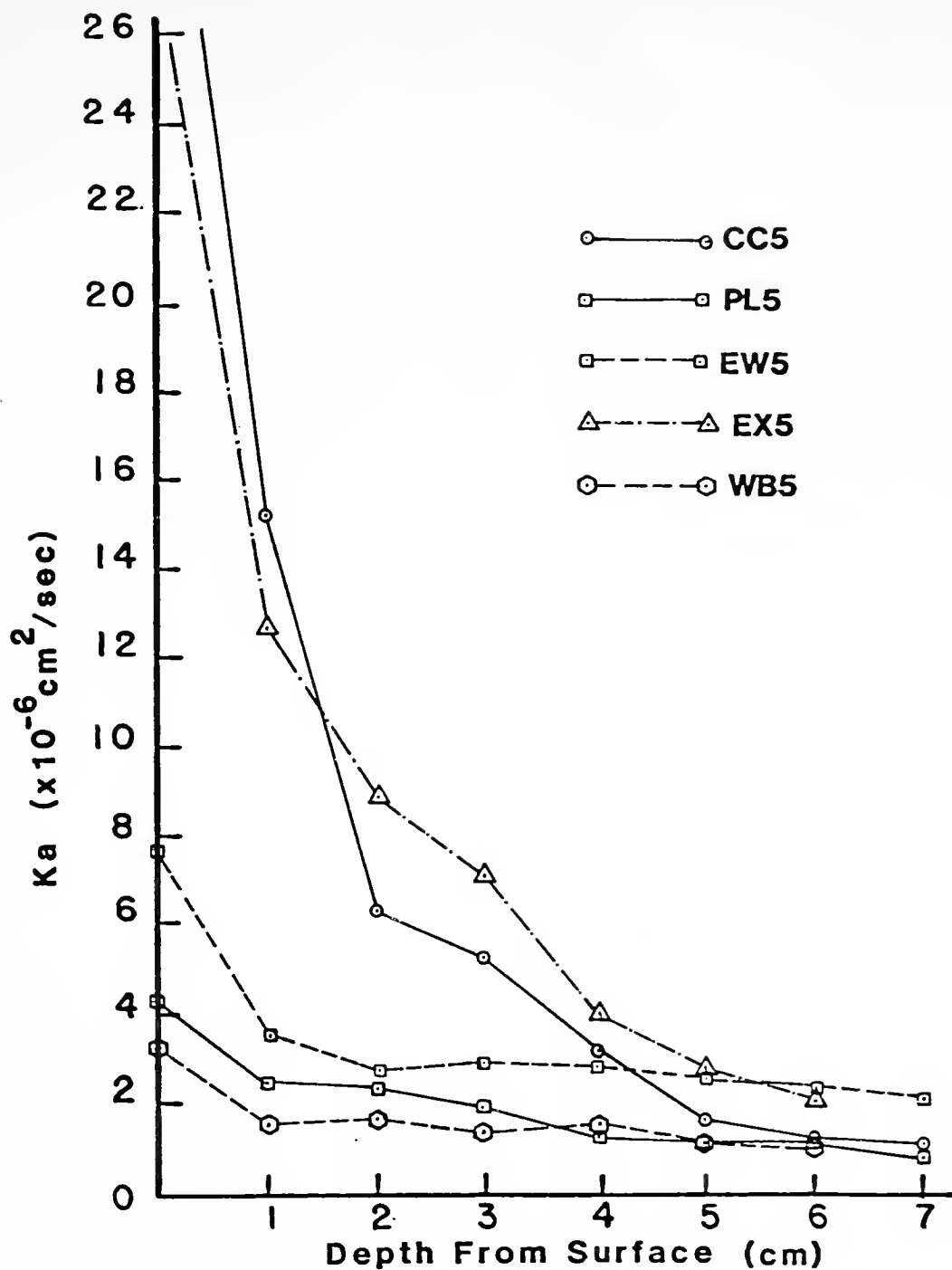


FIG. 17 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED AT 22% R.H. FOR 5 DAYS.

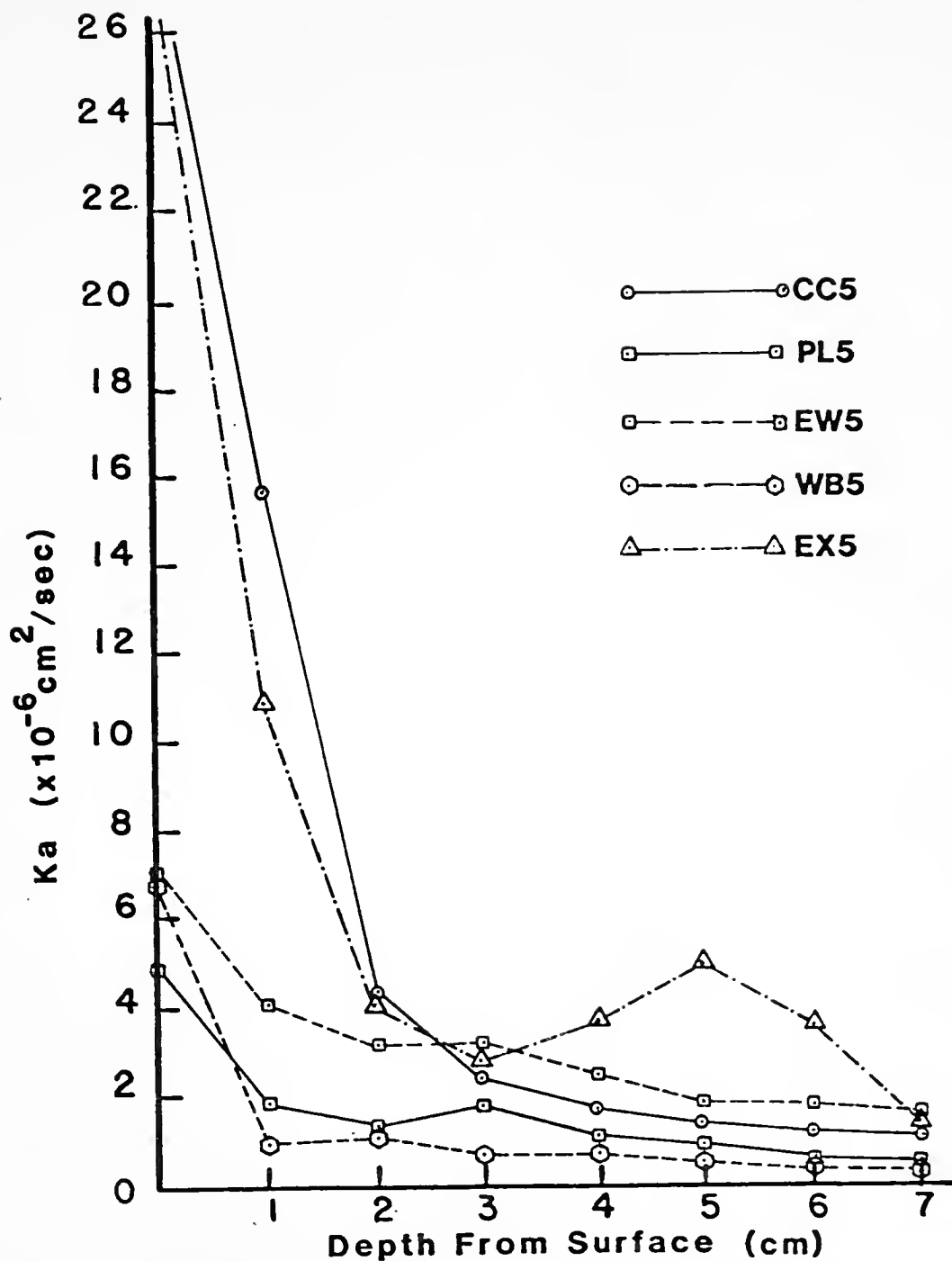


FIG. 18 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED AT 44% R.H. FOR 5 DAYS.

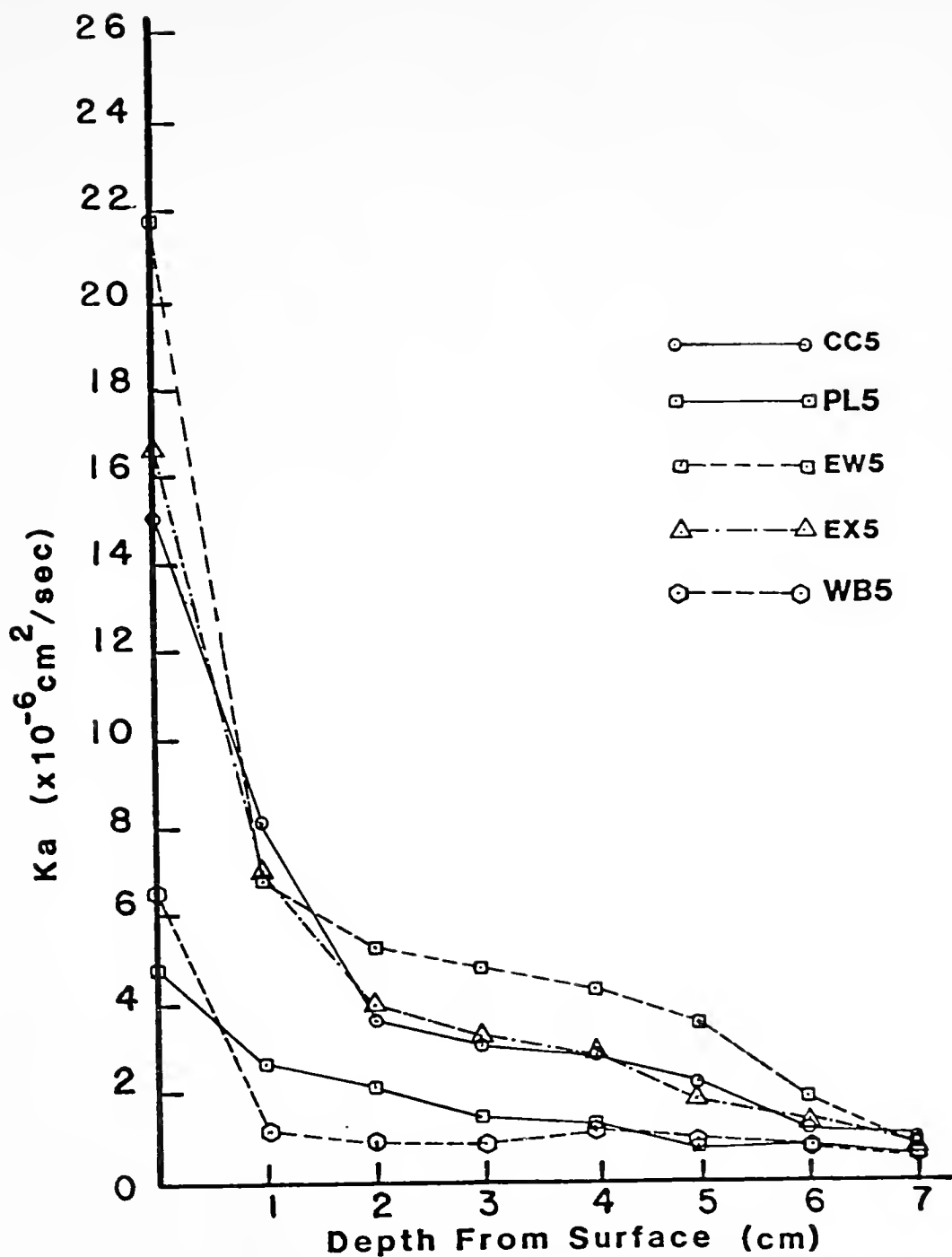


FIG. 19 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED AT 72% R.H. FOR 5 DAYS.

results is that more scatter in the data was observed for the silica sand samples. Unexpected situations, such as the rise in absorptivity at depths four, five, and six for the EX5 sample, shown in Figure 18, were encountered with the silica sand samples. One explanation may be the presence of more abundant, irregular, and large entrapped air bubbles that may have adversely affected the capillary absorption in the relatively small test specimens. Examination of polished surfaces indicated that the silica sand samples contained an average of 11% air as compared with 6.5% for the regular sand samples.

Effect of Atmospheric Conditions

The sensitivity of the absorptivity test to detect differences in the paste properties for samples that were left uncovered for five days at each of the six atmospheric conditions was examined by doing an ANOVA for the layout given in Table 9. This analysis, ANOVA 2, indicated that the main effect, atmospheric conditions, was not significant, which meant that at a given depth, the absorptivity values for the six atmospheric conditions were virtually the same, at the 5% level although significantly different at the 10% level, but as expected, differences were observed between the values for the various depths. This is also pointed out in ANOVA 2. See Figure 20. The result for the samples cured with silica sand is presented in Figure 21. In general, although the shape of the curves is similar to those for

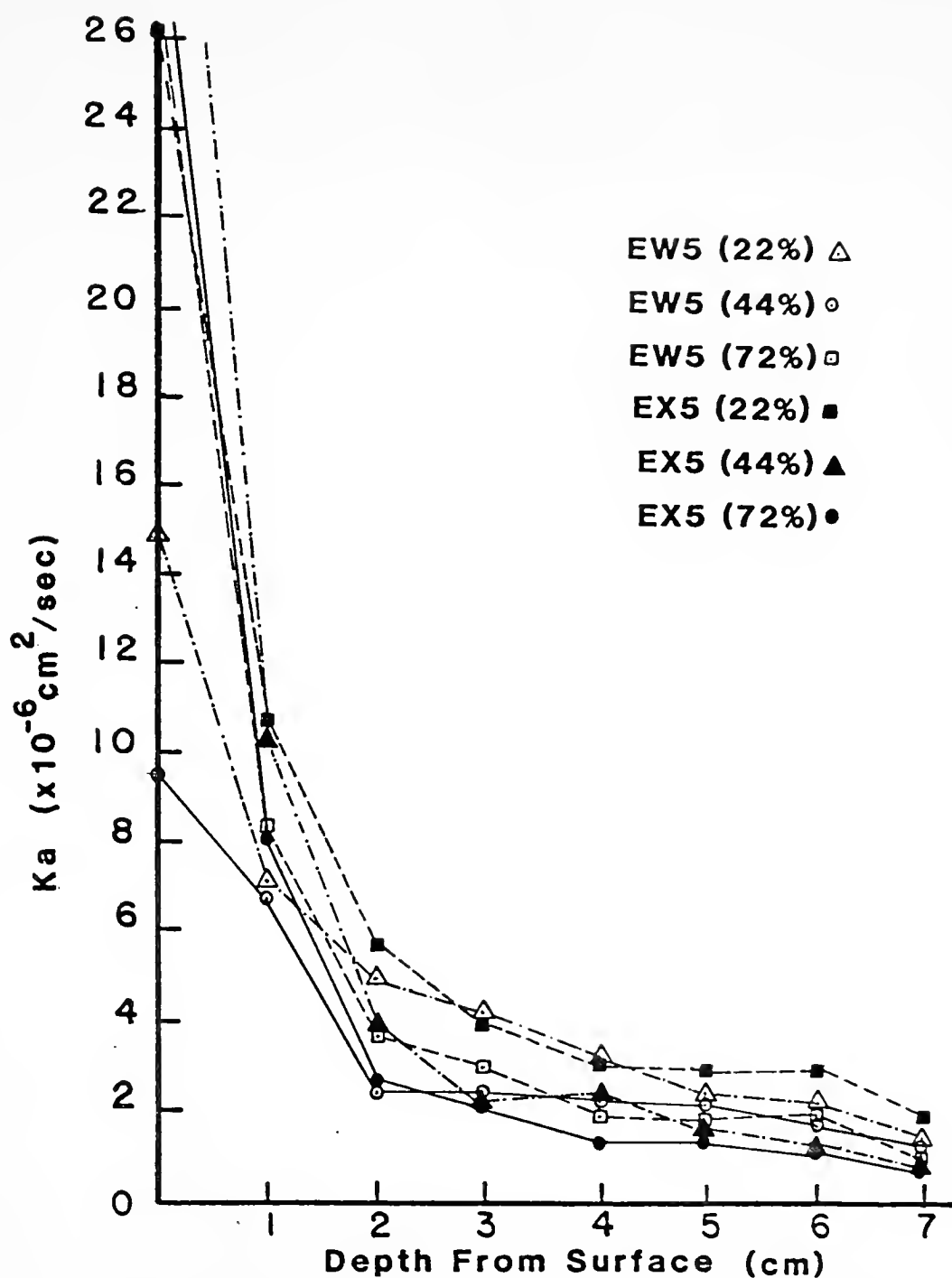


FIG. 20 THE EFFECT OF ATMOSPHERIC CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE WITH REGULAR SAND.

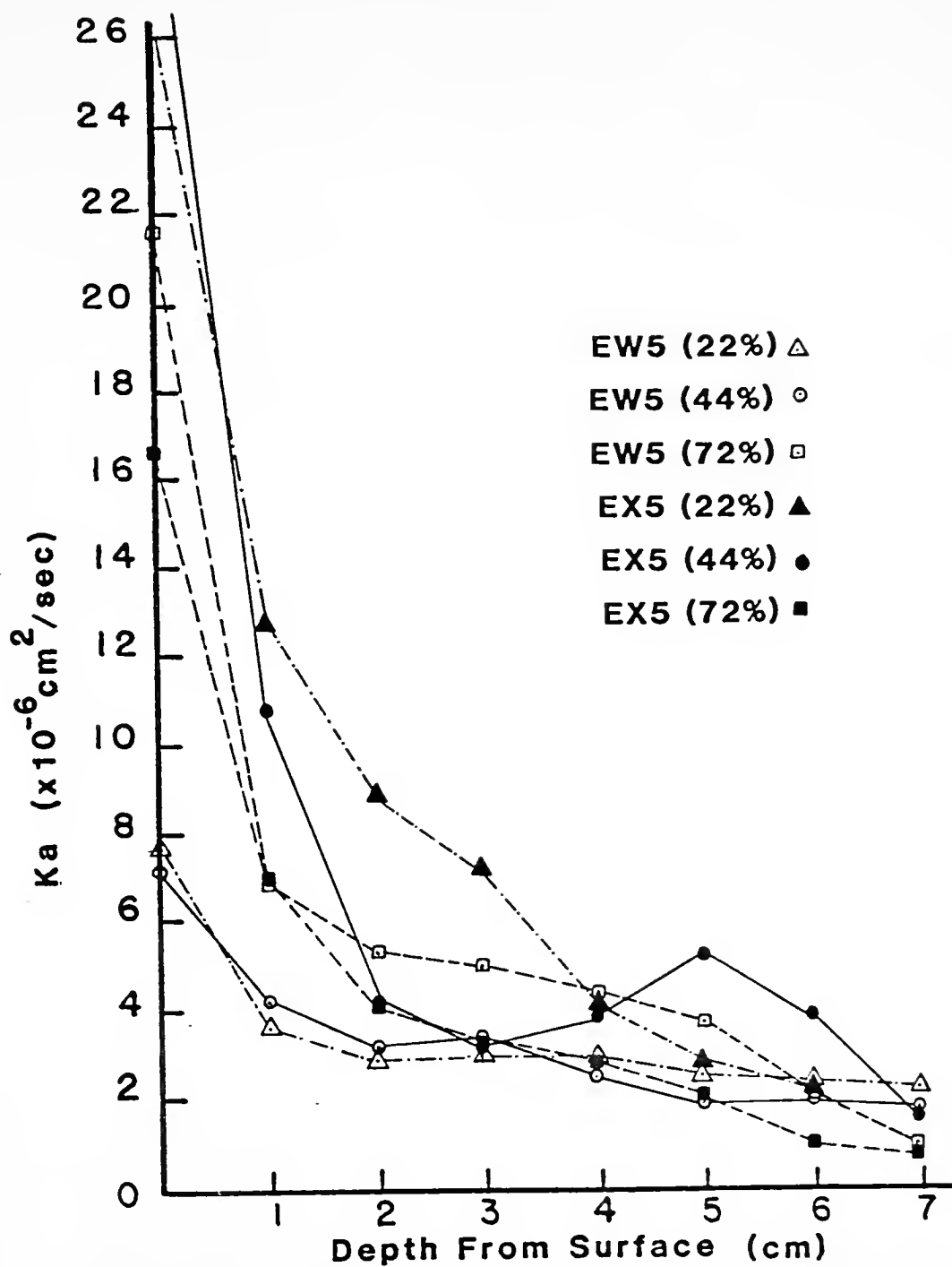


FIG. 21 THE EFFECT OF ATMOSPHERIC CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE WITH SILICA SAND.

regular sand samples, the absorptivity values as a whole are slightly higher. The reason for this is thought to be related to the nature of the entrapped air system in the samples. During the experimentation it was noticed that some of the large irregular air bubbles were like a reservoir where small quantities of water accumulated.

Effect of Duration of Curing

The effect of duration of curing was analyzed by doing an analysis of variance based on the layout in Table 10. The result is labeled ANOVA 3. Again, further analyses of variance had to be done to examine the effect of one factor over the levels of a second factor wherever interaction terms were significant.

ANOVA 3A is an analysis to determine the effect of the three relative humidity conditions on each of the three durations of curing. It should be recalled that the method of curing employed for the evaluation of the effect of duration of curing was the use of wet burlap, and the burlap was wetted twice per day regardless of how quickly it may have dried between wettings. Therefore, as it turned out when the relative humidity was 22%, the burlap was kept damp intermittently, but at 72% relative humidity, it was damp continuously. This, of course, is an important matter to look into, because in actual concrete curing practices where wet burlap is utilized, it is seldom that the burlap is kept damp continuously, and it would be useful to be able to

detect the effect of such shortcomings. According to ANOVA 3A, the effect of relative humidity on the absorptivity of the WB1 and WB3 samples was significant, but not for WB5. This is illustrated in Figures 22, 23 and 13. Note that the absorptivity values for WB1 at 72% R.H. were markedly smaller than they were at either 22% or 44% R.H. For WB3 the same is true, but to a reduced extent, and for WB5 there was no difference among the three relative humidity conditions. One peculiar result observed in Figures 22 and 23 is that higher absorptivity values are seen at 44% R.H. than at 22% R.H. This is the opposite of what was expected, and the reason may be that the various burlap covers were not wetted identically, and the burlap covers used at the 22% R.H. condition may well have received more water each time they were wetted. The samples that were cured for 5 days were not affected by the three relative humidity conditions, perhaps because over that length of time enough water may have been acquired by the surfaces during the nine wettings of the burlap covers, thereby making the effects of the relative humidity conditions insignificant.

Examination of changes in absorptivity with depth for each of the three durations of curing at 20% R.H. condition was done through ANOVA 3B. The analysis shows that changes in absorptivity with depth were significant only for one day of curing. For three and five days, the changes with depth were not significant, and generally the absorptivity values

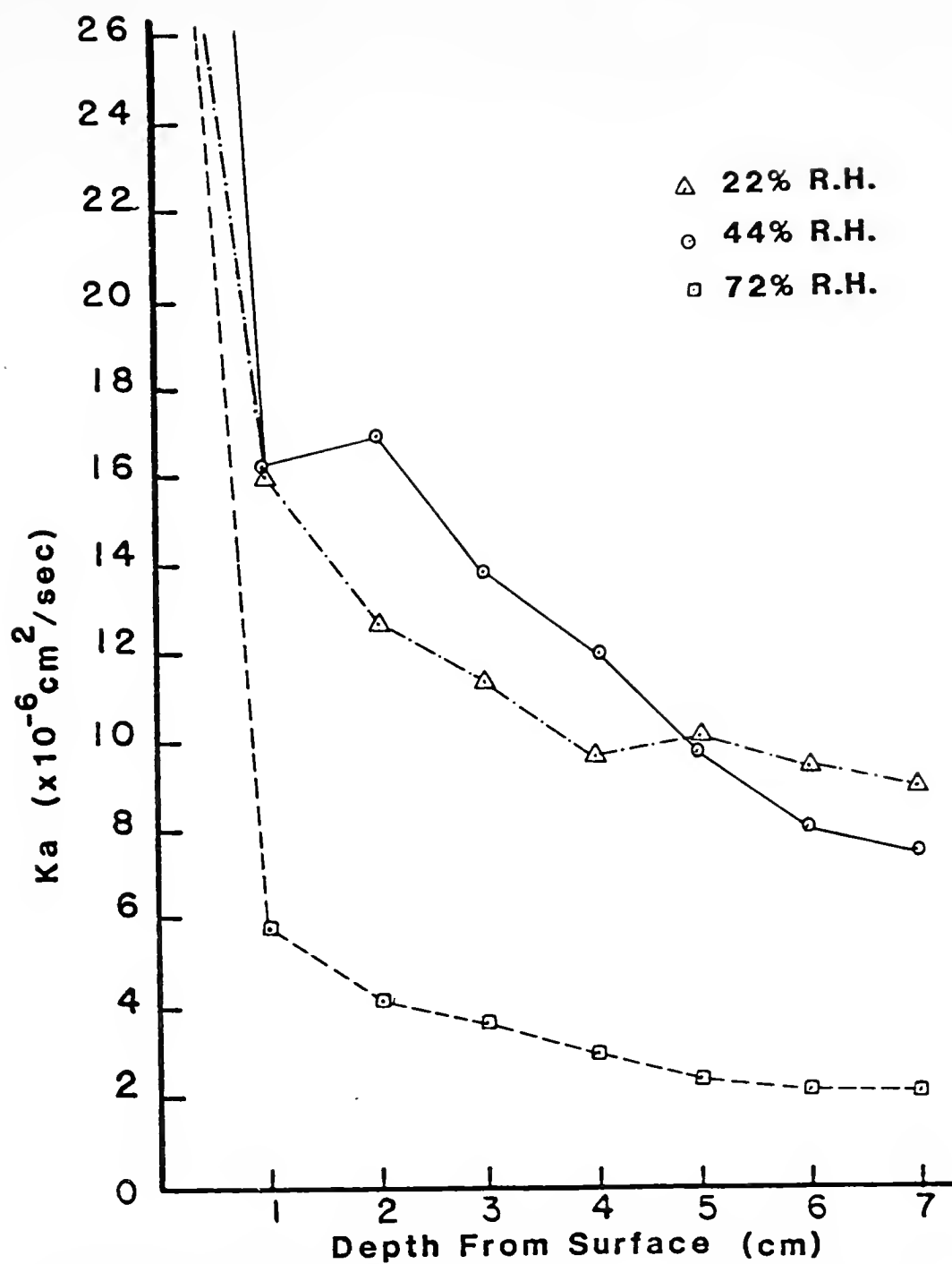


FIG. 22 EFFECT OF RELATIVE HUMIDITY ON ABSORPTIVITY FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP FOR 1 DAY.

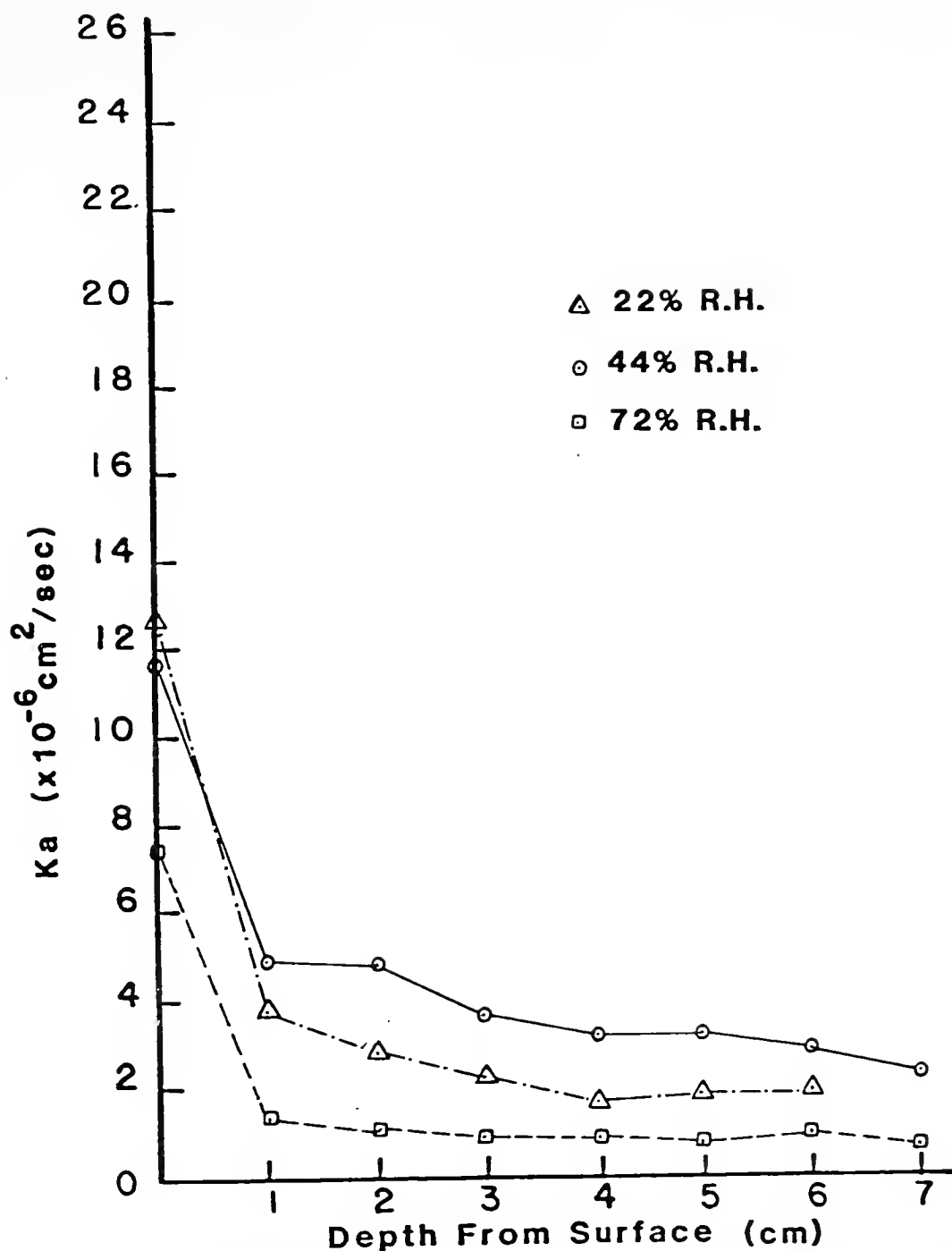


FIG. 23 EFFECT OF RELATIVE HUMIDITY ON ABSORPTIVITY FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP FOR 3 DAYS.

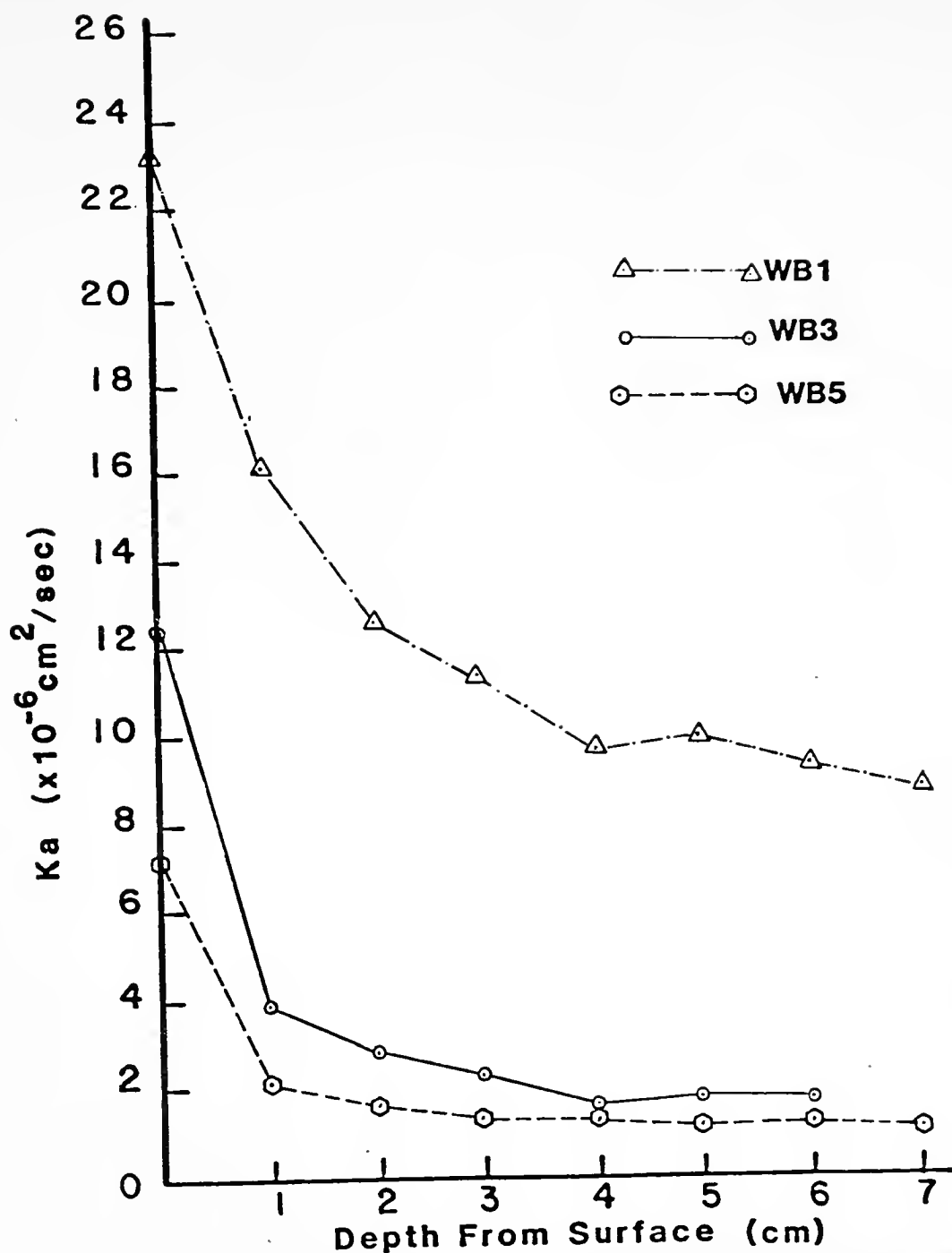


FIG. 24 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 22% R.H.

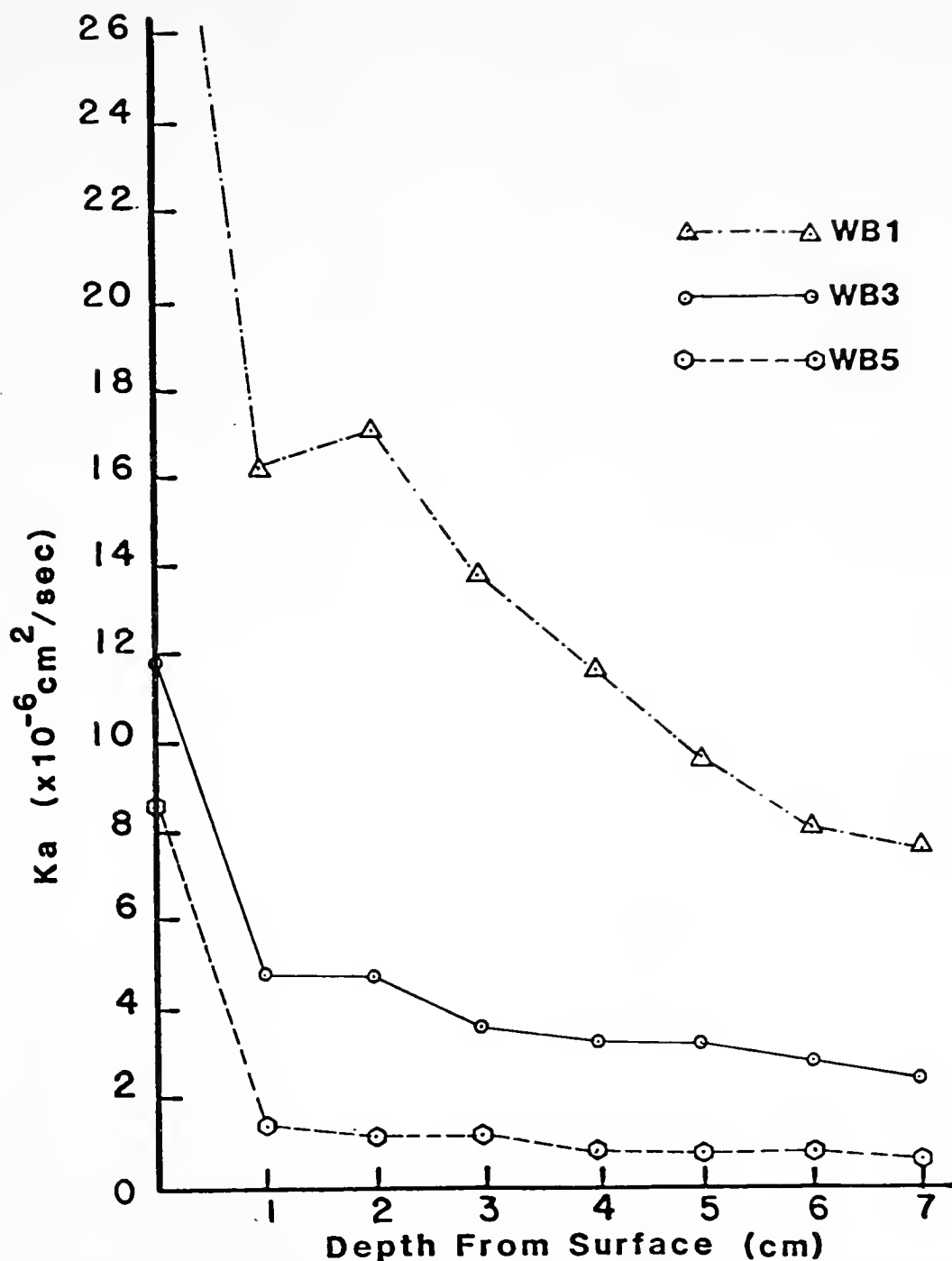


FIG. 25 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 44% R.H.

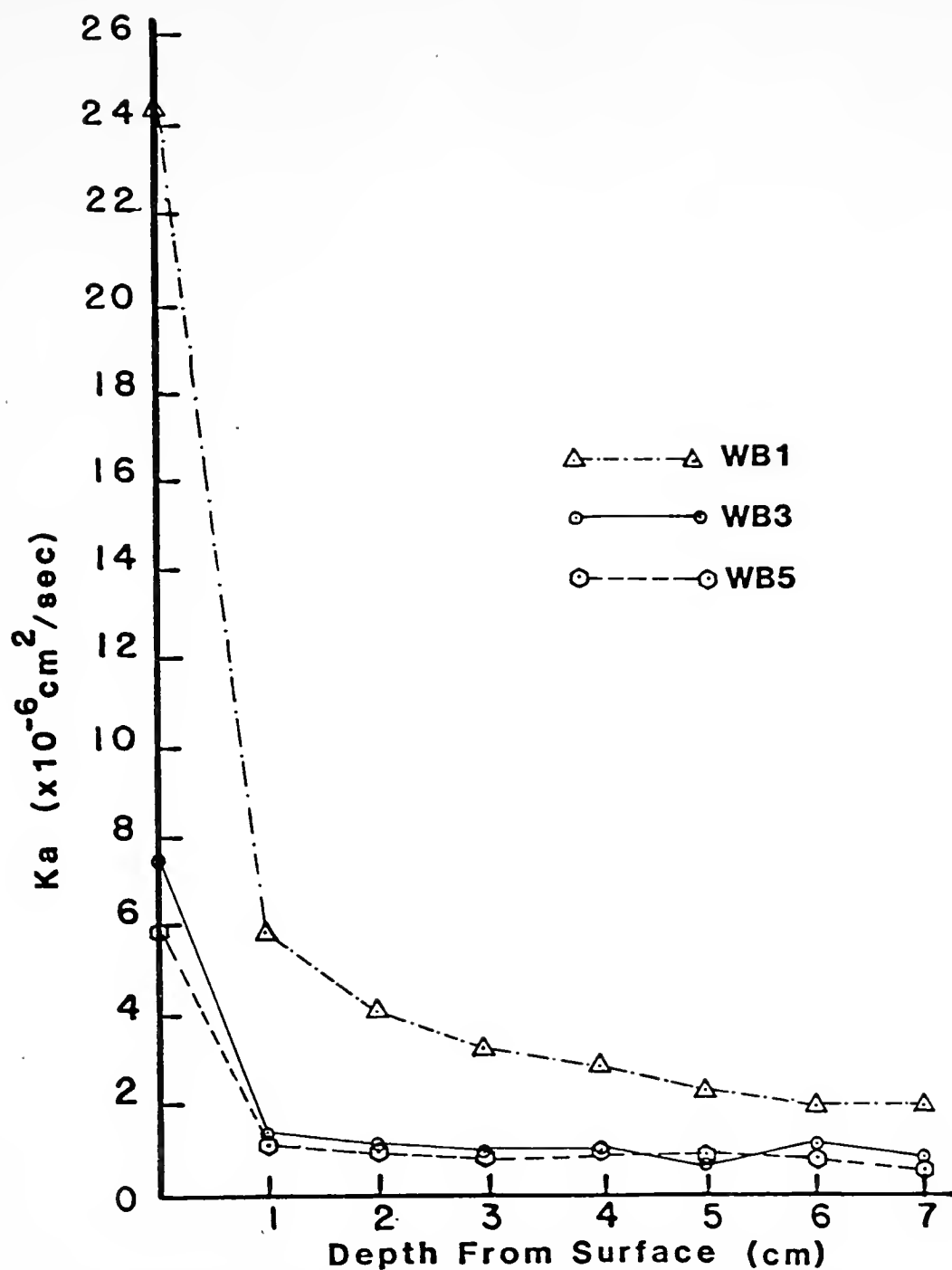


FIG. 26 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 72% R.H.

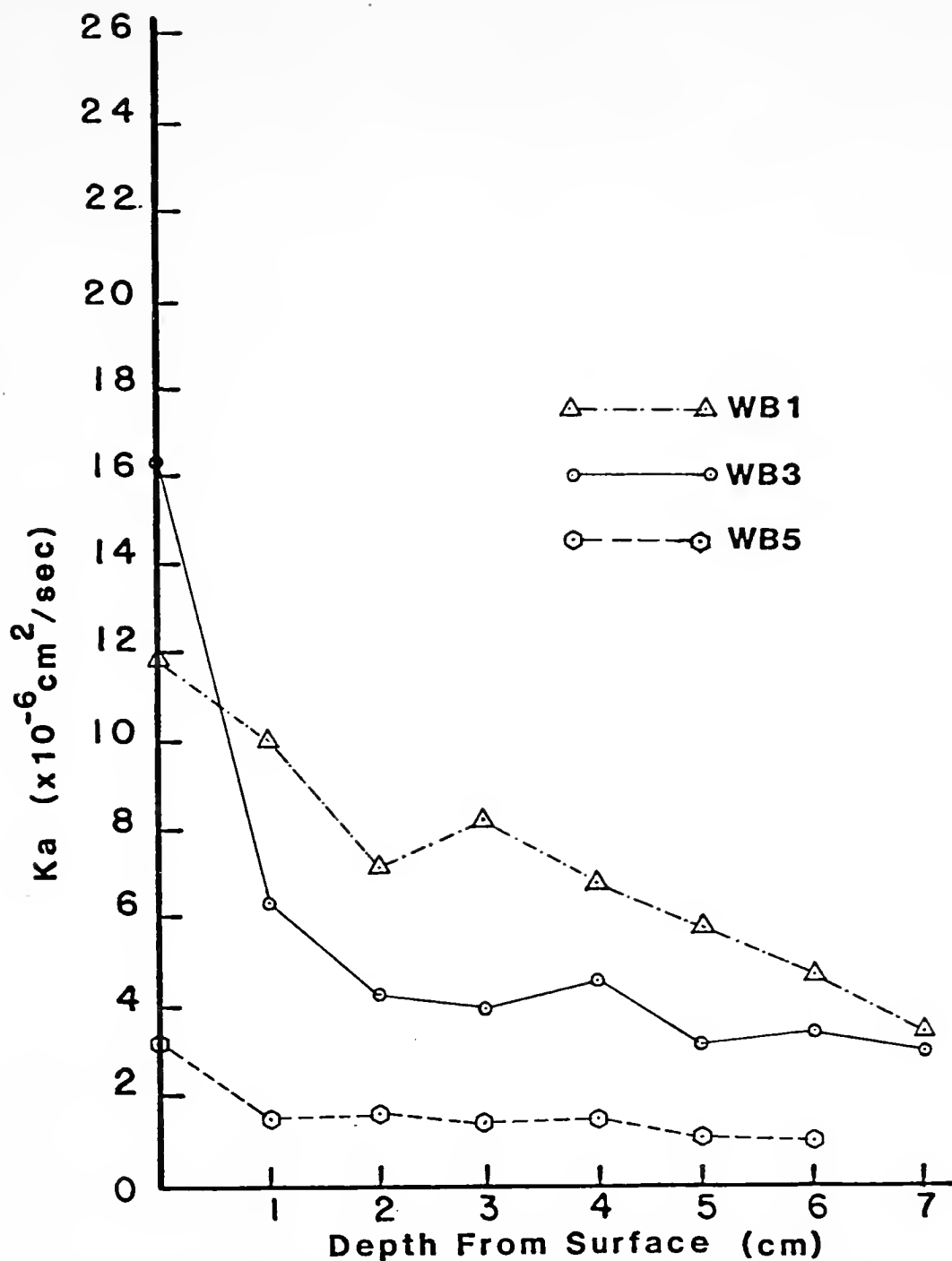


FIG. 27 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED WITH WET BURLAP AT 22% R.H.

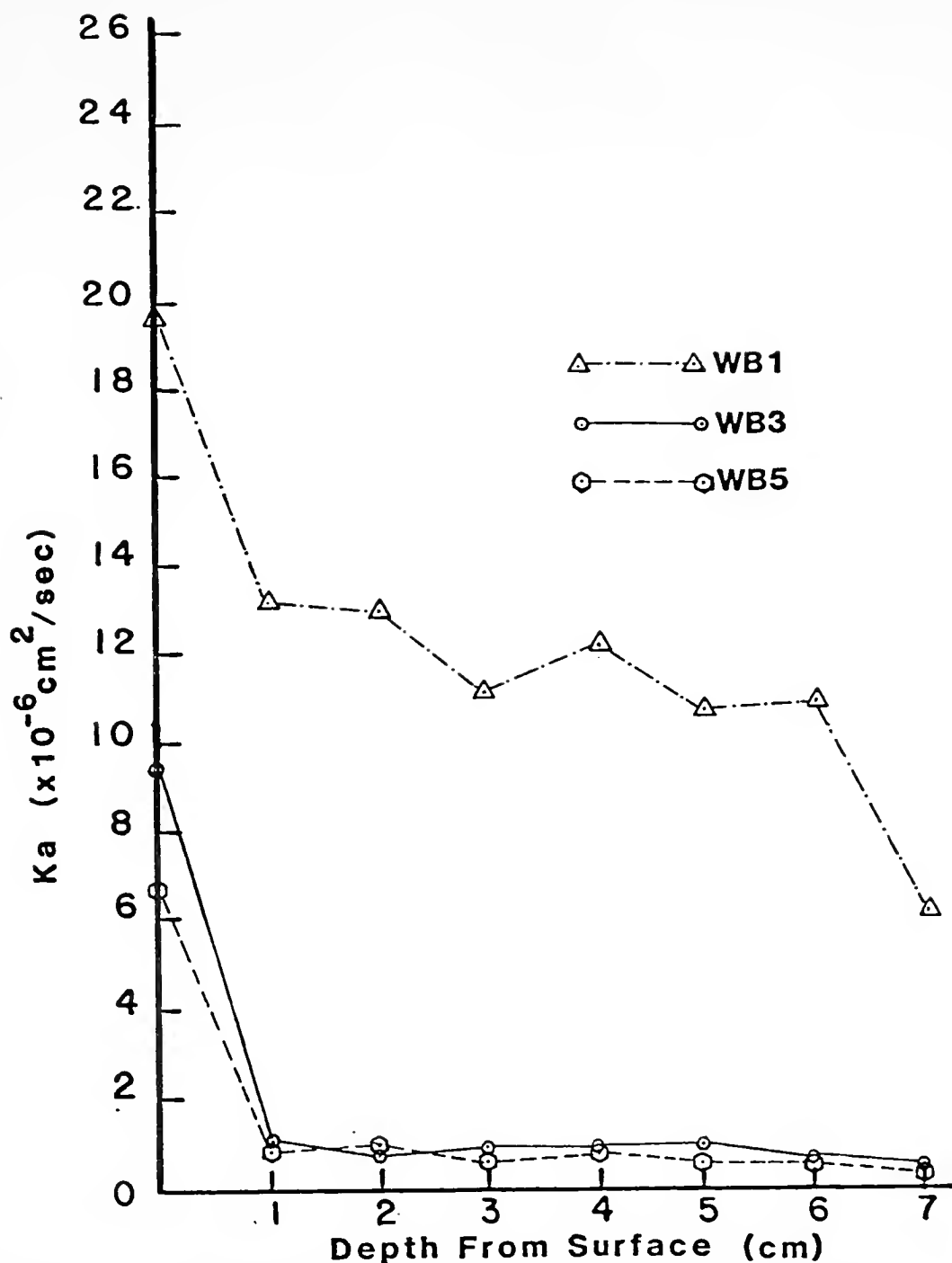


FIG. 28 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED WITH WET BURLAP AT 44% R.H.

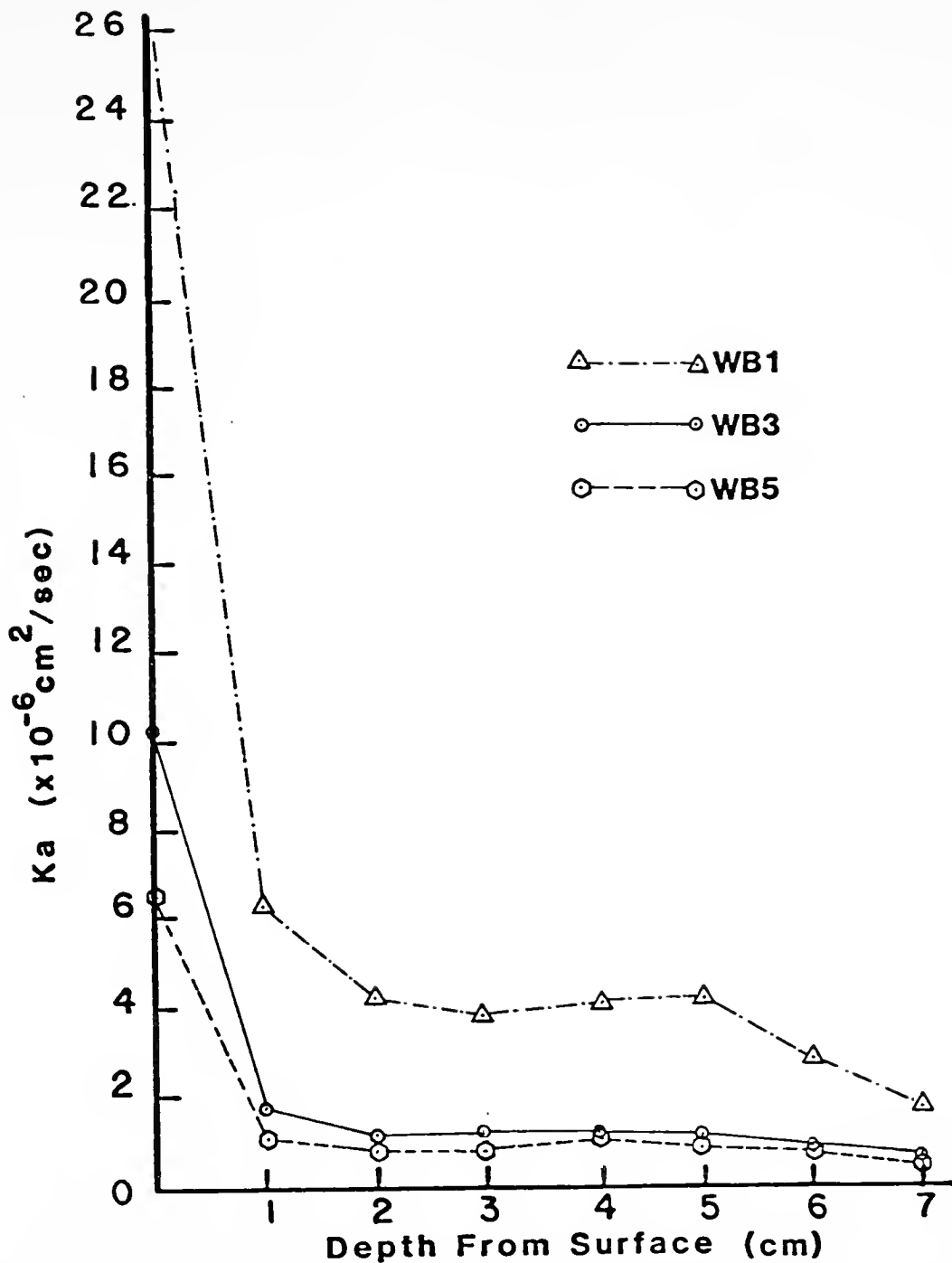


FIG. 29 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR SAMPLES MADE OF SILICA SAND AND CURED WITH WET BURLAP AT 72% R.H.

were essentially the same. See Figures 24-26. It is not known why the significant change in absorptivity with depth existed for the WB1 samples at 22% and 44% R.H. conditions.

The results for the silica sand samples are given in Figures 27-29. Comparison of these figures with Figures 24-26 respectively, shows the similarity of the results from the two sets of samples made with the two different types of sand.

Non-evaporable Water Test Results

In spite of promising preliminary results obtained during the early stages of this project, when possible test methods were evaluated, the non-evaporable water test did not produce the expected results. In general the test's sensitivity to changes induced in the mortar samples by curing was limited to detecting the effects of relative humidity and duration of curing.

The average values of non-evaporable water contents for all the samples are presented in Tables 18-21. The results for the silica sand samples are generally higher than those for the regular sand because of the difference in temperature at which the specimens were heated to remove their non-evaporable water. The data were subjected to analyses of variance based on the layouts in Tables 8-10. The analyses for evaluating the factors, method of curing, and atmospheric conditions did not produce meaningful results except for significant differences observed between the two extreme

Table 18. Non-evaporable Water Test Results for Samples Made of Regular Sand and Cured for 5 Days Under Different Curing Conditions and at Different Relative Humidities

Relative Humidity	Curing Condition	Percent Loss on Heating at 550°C*							
		Depth from Surface (cm)							
		1st	2nd	3rd	4th	5th	6th	7th	8th
22%	WB	2.67	2.86	2.90	2.88	2.82	2.89	2.86	2.80
	PL	2.87	2.93	2.90	3.06	2.94	3.11	3.05	2.89
	CC	2.23	2.59	2.63	2.81	2.80	2.90	2.91	2.85
	EX	2.37	2.65	2.81	2.84	2.78	2.84	2.84	2.84
	EW	2.17	2.59	2.38	2.66	2.70	2.89	2.86	2.70
44%	WB	2.93	3.67	3.92	3.87	3.87	3.68	3.80	3.45
	PL	3.83	3.98	4.05	3.97	3.82	4.15	3.58	3.15
	CC	2.71	3.26	3.79	3.60	3.90	3.64	3.96	3.51
	EX	3.08	3.26	3.45	3.67	3.25	3.53	3.54	3.21
	EW	3.20	3.37	3.80	3.63	3.74	3.69		
72%	WB	3.52	4.03	4.09	4.03	3.97	3.85	3.88	3.31
	PL	3.47	3.62	3.72	3.84	3.80	3.96	4.05	3.03
	CC	3.33	3.36	4.02	3.76	3.83	4.13	3.83	3.27
	EX	2.64	3.17	3.59	3.90	3.70	3.81	3.99	3.60
	EW	3.21	3.41	3.64	3.25	3.50	3.62	3.43	3.31

*Percent by weight of oven dried mortar; average of two observations

Table 19. Non-evaporable Water Test Results for Samples Made of Regular Sand and Cured with Wet Burlap for Different Lengths of Time and at Different Relative Humidities

Relative Humidity	Duration of Curing (Days)	Percent Loss on Heating at 550°C*							
		Depth from Surface (cm)							
		1st	2nd	3rd	4th	5th	6th	7th	8th
22%	1	1.97	2.09	2.12	2.12	2.13	2.16	2.20	1.97
	3	2.45	2.70	2.62	2.58	2.73	2.53	2.71	2.42
	5	2.67	2.86	2.90	2.88	2.82	2.89	2.86	2.80
44%	1	2.09	2.12	2.13	2.08	2.21	2.22	2.26	2.06
	3	2.57	2.60	2.59	2.63	2.71	2.65	2.72	2.41
	5	2.93	3.67	3.92	3.87	3.87	3.68	3.80	3.45
72%	1	2.87	3.24	3.16	3.38	3.23	3.33	3.30	2.45
	3	3.59	4.01	3.96	3.89	4.01	4.03	3.79	3.09
	5	3.52	4.03	4.09	4.03	3.97	3.85	3.88	3.31

*Percent by weight of oven dried mortar; average of two observations

Table 20. Non-evaporable Water Test Results for Samples Made of Silica Sand and Cured for 5 Days Under Different Curing Conditions and at Different Relative Humidities

Relative Humidity	Curing Condition	Percent Loss on Heating at 1050°C*							
		Depth from Surface (cm)							
		1st	2nd	3rd	4th	5th	6th	7th	8th
22%	WB	3.83	3.84	3.82	3.84	3.82	3.85	3.80	
	PL	4.01	3.95	4.01	4.02	4.08	3.96	3.86	
	CC	3.49	3.88	3.87	3.98	3.90	3.88	3.83	
	EX	3.67	3.75	3.84	3.91	3.91	3.85	3.70	
	EW	3.69	3.83	3.91	3.87	3.93	3.89	3.86	
44%	WB	4.27	4.58	4.61	4.56	4.58	4.59	4.62	4.24
	PL	3.83	3.98	3.99	3.95	3.97	3.97	3.94	
	CC	3.93	4.03	4.10	4.11	4.06	4.14		
	EX	4.04	4.23	4.25	4.27	4.28	4.21	4.28	4.24
	EW	4.04	4.19	4.23	4.29	4.31	4.40	4.37	4.15
72%	WB	4.29	4.60	4.60	4.63	4.55	4.61	4.63	4.35
	PL	4.29	4.35	4.34	4.42	4.39	4.47	4.34	4.14
	CC	3.88	4.17	4.27	4.29	4.24	4.30	4.30	4.12
	EX	4.04	4.19	4.27	4.25	4.29	4.24	4.22	4.18
	EW	4.02	4.27	4.21	4.24	4.37	4.31	4.31	4.11

*Percent by weight of oven dried mortar; average of two observations

Table 21. Non-evaporable Water Test Results for Samples Made of Silica Sand and Cured with Wet Burlap for Different Lengths of Time and at Different Relative Humidities

Relative Humidity	Duration of Curing (Days)	Percent Loss on Heating at 1050°C*							
		Depth from Surface (cm)							
		1st	2nd	3rd	4th	5th	6th	7th	8th
22%	1	2.98	2.96	3.03	2.88	3.00	3.06	2.98	
	3	3.52	3.55	3.66	3.62	3.63	3.54	3.42	
	5	3.82	3.84	3.82	3.84	3.82	3.88	3.80	
44%	1	2.92	3.04	3.06	3.03	3.03	3.07	3.27	3.19
	3	3.46	3.66	3.61	3.63	3.73	3.69	3.64	3.45
	5	4.27	4.58	4.61	4.56	4.58	4.59	4.62	4.24
72%	1	3.70	4.10	4.29	4.17	4.18	4.11	4.08	3.70
	3	3.98	4.29	4.29	4.32	4.28	4.27	4.29	4.04
	5	4.29	4.60	4.60	4.63	4.55	4.61	4.63	4.35

*percent by weight of oven dried mortar; average of two observations

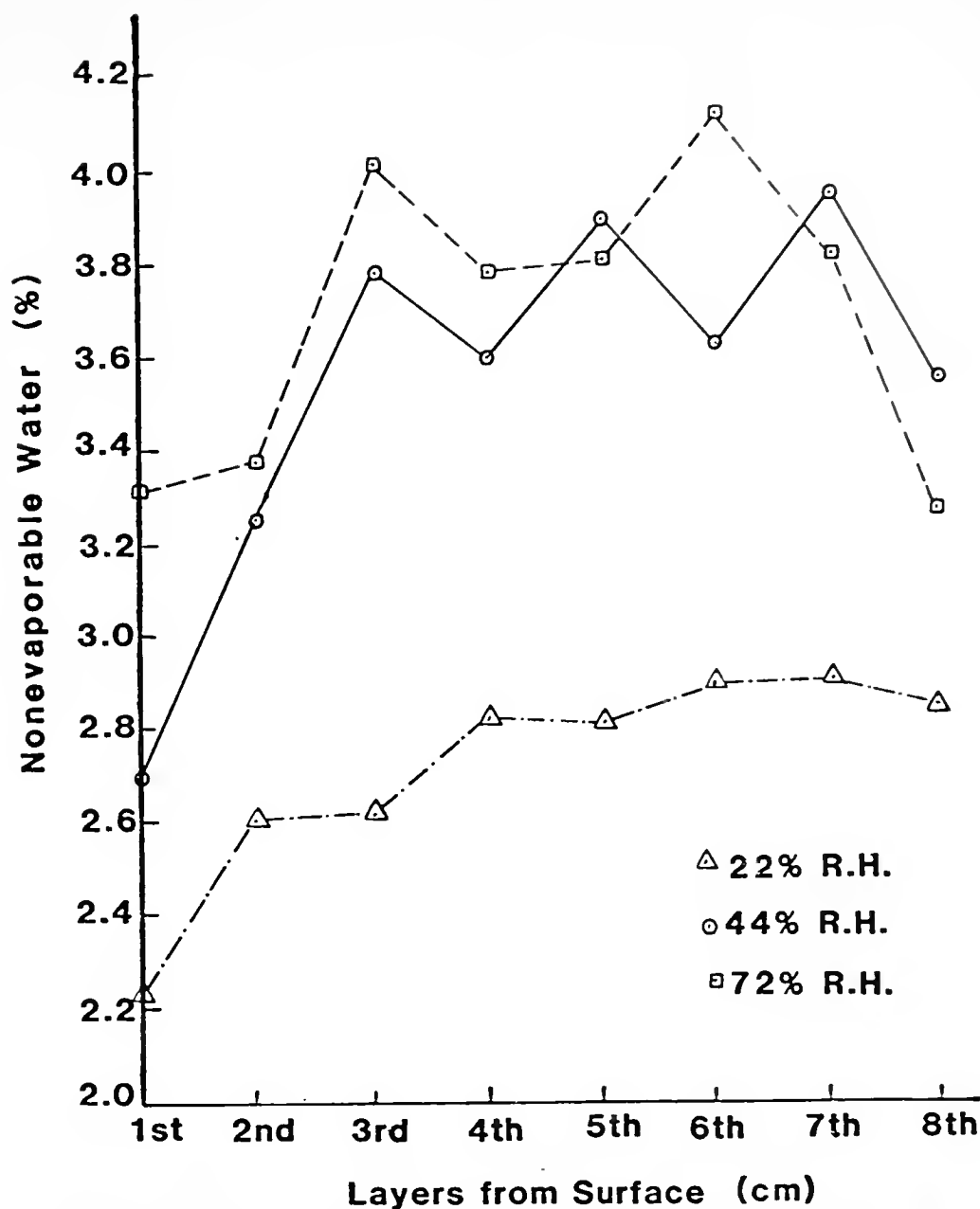


FIG. 30 EFFECT OF RELATIVE HUMIDITY ON CHANGE IN NON-EVAPORABLE WATER CONTENT FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH CURING COMPOUND FOR 5 DAYS.

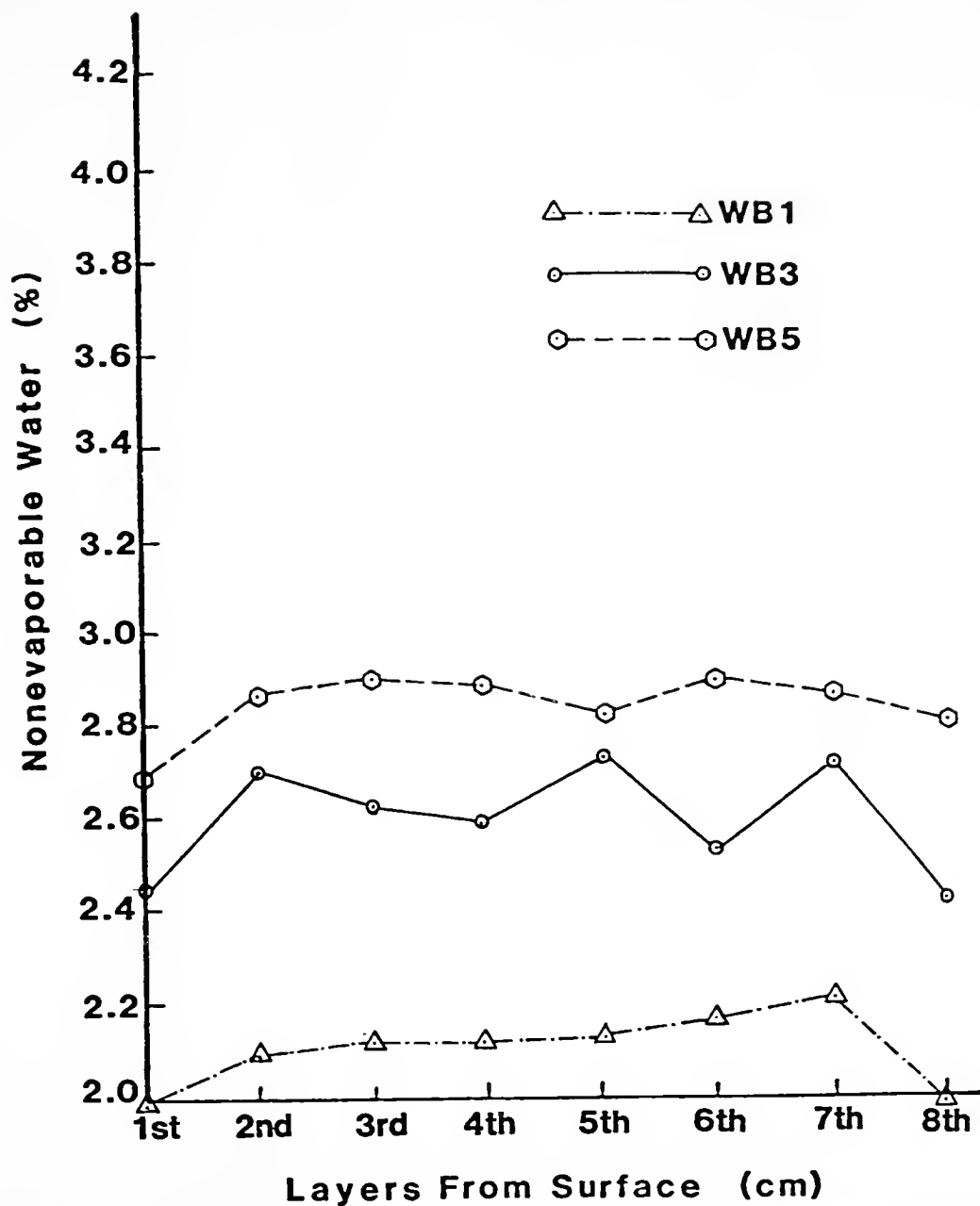


FIG. 31 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN NON-EVAPORABLE WATER WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 22% R.H.

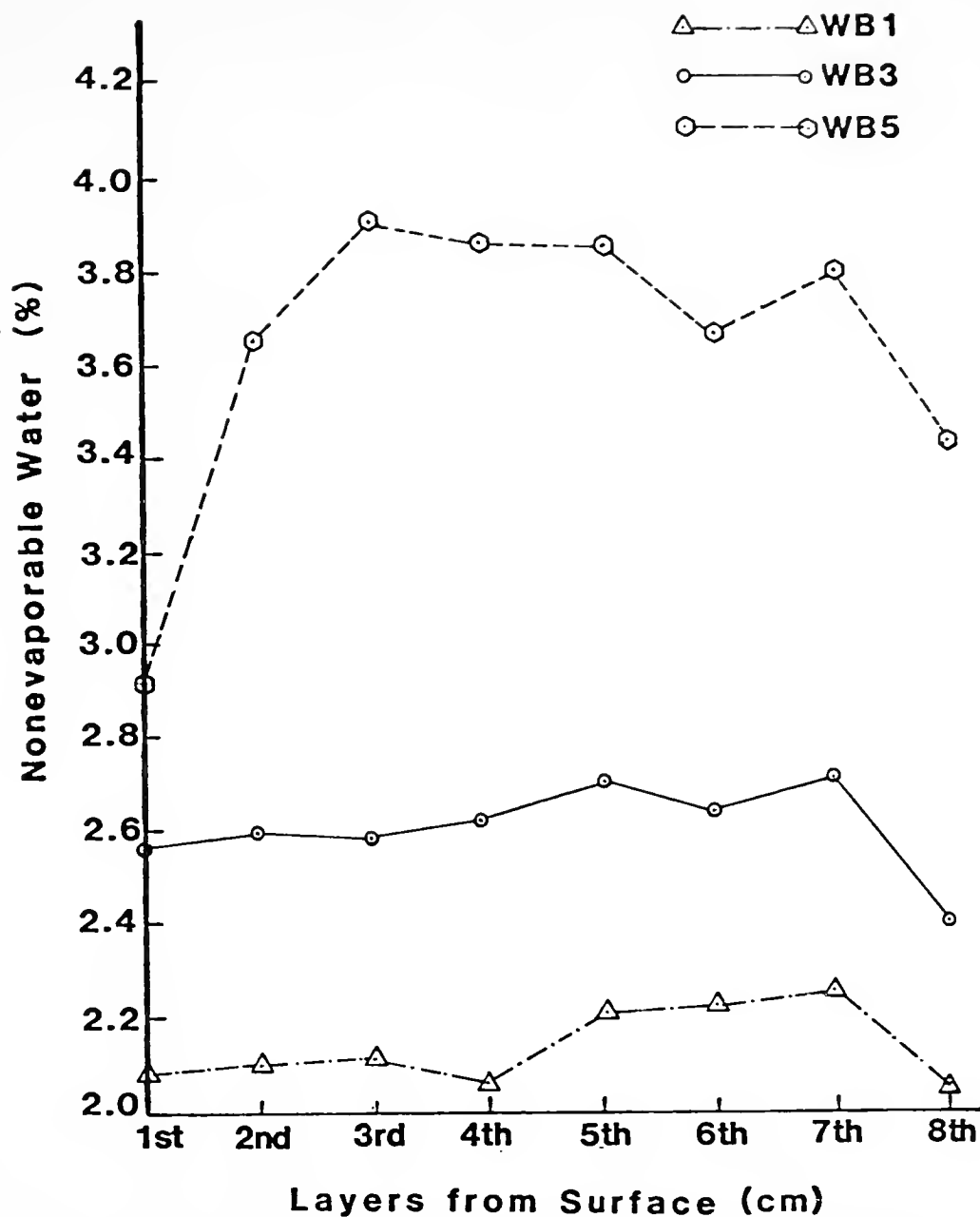


FIG. 32 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN NON-EVAPORABLE WATER WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 44% R.H.

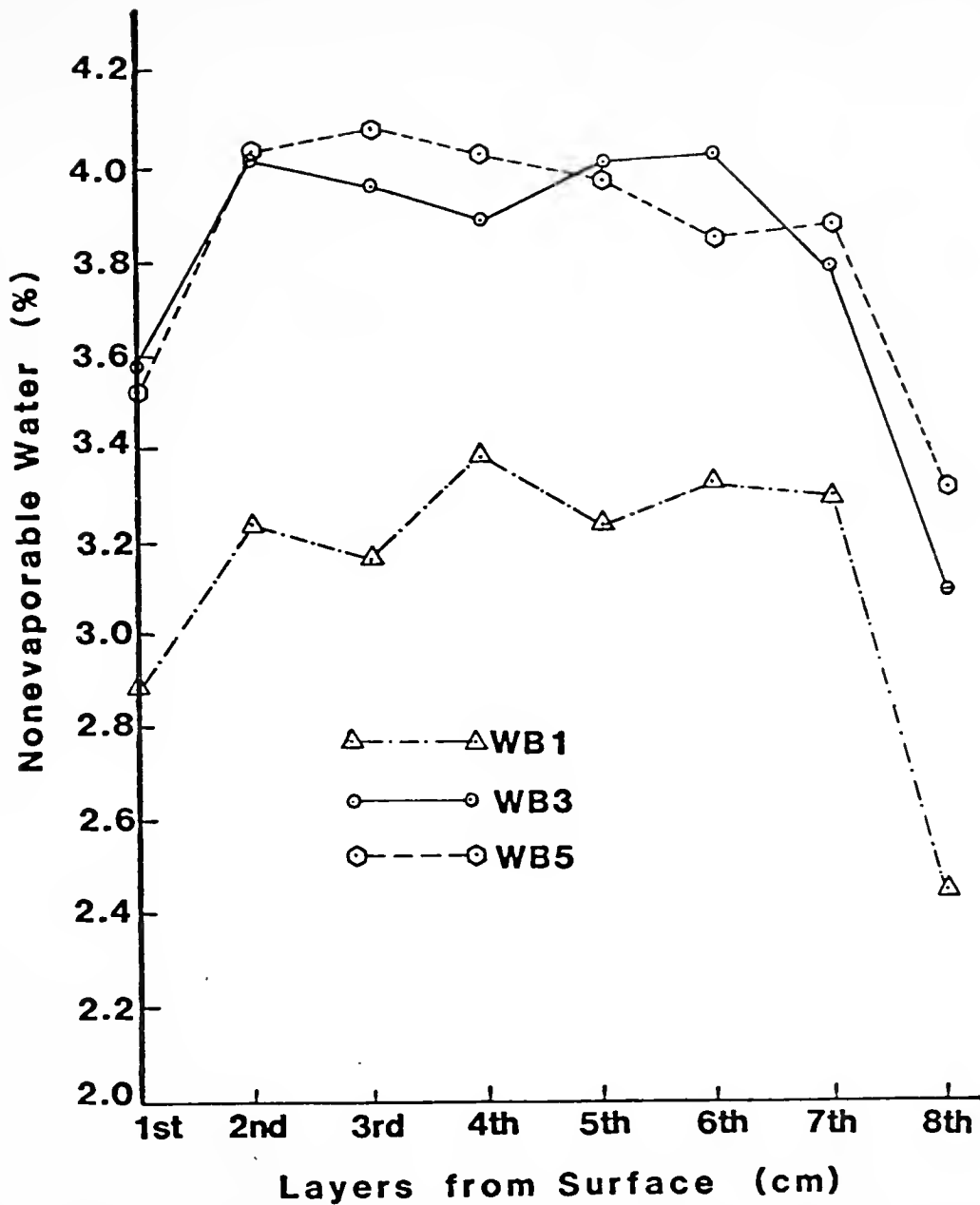


FIG. 33 EFFECT OF DIFFERENT DURATIONS OF CURING ON CHANGE IN NON-EVAPORABLE WATER WITH DEPTH FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP AT 72% R.H.

relative humidity conditions for each method of curing. An example is illustrated in Figure 30. Curing at the 22% R.H. condition produced significantly lower non-evaporable water content values compared to those cured at 72%, and the 44% R.H. condition results were somewhere in between.

As demonstrated by ANOVA 4 and N-K 4 in the appendix, duration of curing had a strong influence on non-evaporable water content of the regular sand samples. The results are illustrated in Figures 31-33. Similar results were obtained for the silica sand samples.

Abrasion Test Results

In Tables 22 and 23 the average volumes of the eight abraded cavities for each of the samples cured under the various curing conditions and durations are presented. As mentioned earlier, the volumes were determined by using an oil base modeling clay in keeping with the recommendations of ASTM C418.

Effect of Method of Curing

The sensitivity of the abrasion test to detect differences in the quality of the mortar surfaces as affected by the four methods of curing at the three relative humidity conditions was examined by doing an analysis of variance according to the layout in Table 11, and Equation 5. The analysis, ANOVA 5, shows that the quality of the surfaces, i.e., their abrasion resistance, was affected by the four

Table 22. Abrasion Test Results for Samples Made of Regular Sand and Cured Under Different Conditions for 5 Days

Relative Humidity	Average Volume of Abraded Cavities (cu cm) for Different Curing Conditions				
	WB5	PL5	CC5	EX5	EW5
22%	4.26	4.63	7.63	7.08 (12.24) *	5.46
44%	4.76	4.88	6.93 (11.36)	7.59	5.96
72%	4.46	4.99 (9.12)	6.48	6.65	6.77

*The numbers in parentheses are results for samples made with graded silica sand from Ottawa, Illinois

Table 23. Abrasion Test Results for Samples Made of Regular Sand Cured with Wet Burlap for Different Lengths of Time

Relative Humidity	Average Volume of Abraded Cavities (cu cm) for Different Durations of Curing		
	1 Day	3 Days	5 Days
22%	8.53	5.41	4.26
44%	8.55	5.29	4.76
72%	8.81	5.50	4.46

methods of curing, and by the three relative humidity conditions. Also, as indicated by the significance of the interaction term, the effect of the 3 R.H. conditions was not the same on the four methods of curing. ANOVA 5A is an analysis for the four methods of curing at each of the 3 R.H. conditions, and it shows that at all 3 R.H. conditions there were significant differences in the four methods of curing. It is obvious that the method of curing, or how effective the method was, would be critical at low R.H. conditions where prevention of evaporation of water from the fresh mortar surfaces was certainly crucial, but the results of the abrasion tests show that for R.H. conditions as high as 72%, the methods of curing did produce significantly different surfaces. The differences between the four methods of curing at each of the three R.H. conditions were examined by running a Newman-Keuls analyses as shown in N-K 5A. The result shows that at 22% and 44% R.H. conditions there was no significant difference between the abrasion resistance of the surfaces that were cured with wet burlap and with plastic cover, but the other two curing methods produced significantly different surfaces. At 72% R.H. the surfaces that were cured with curing compound and with no cover were essentially the same, and the other two methods produced surfaces with different abrasion resistances. All of what is stated above is illustrated in Figure 34. It should be recalled that similar results were obtained from the ab-

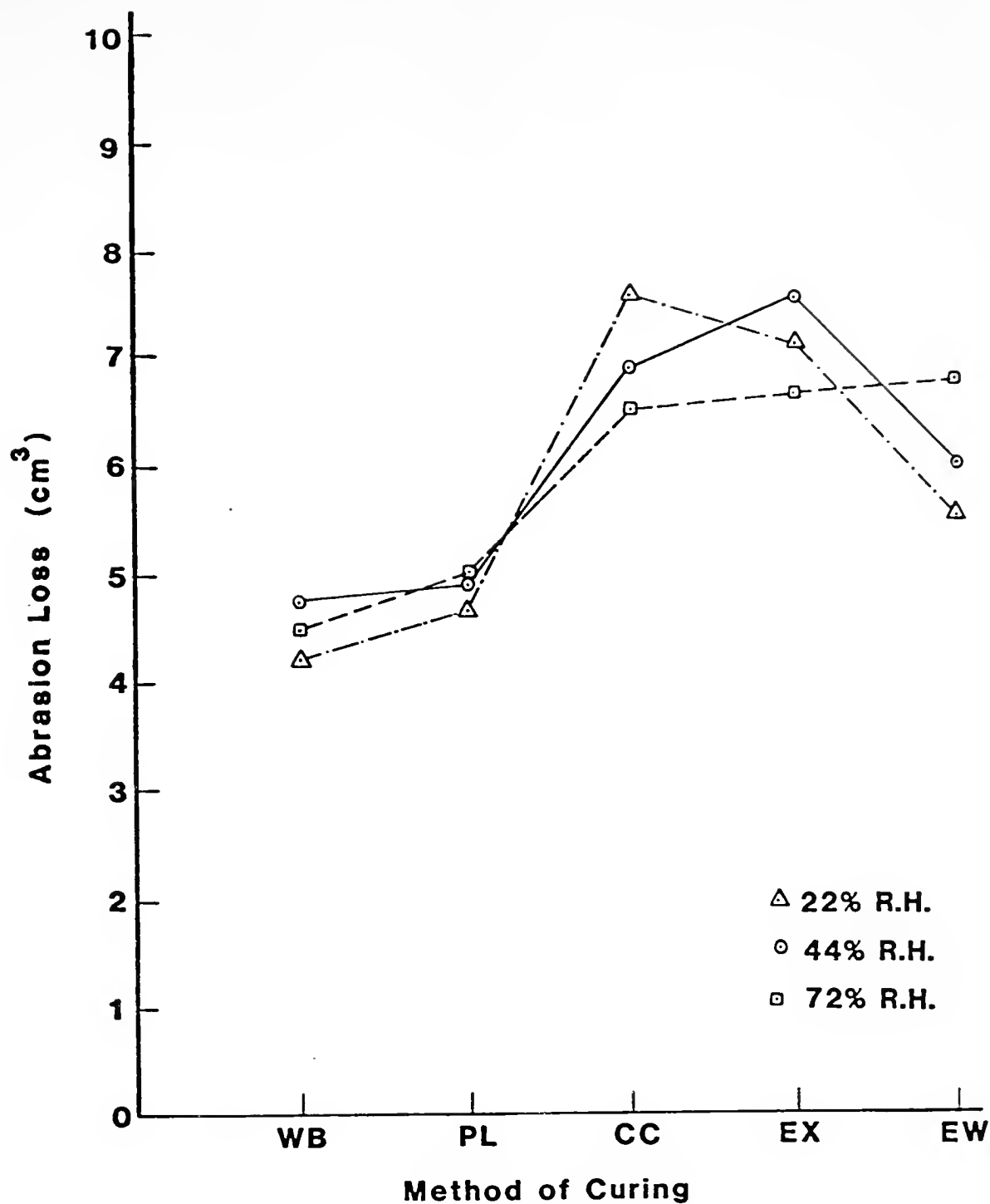


FIG. 34 EFFECT OF RELATIVE HUMIDITY ON ABRASION LOSS FOR SAMPLES MADE OF REGULAR SAND AND CURED UNDER DIFFERENT CONDITIONS.

sorptivity tests. As was done with the plots dealing with the absorptivity test results, the data from the samples cured with no cover in windy conditions (EW) were included in Figure 34, and again, consistent with what was observed in Figures 10-13, the EW5 samples had surfaces not as good as the WB5 or PL5 samples, but for the most part better than the CC5 and EX5 samples.

Effect of Atmospheric Conditions

As shown by ANOVA 6, run according to Table 12 and Equation 6, the six atmospheric conditions had a significant effect on the abrasion resistances of the surfaces. Further analysis by means of the Newman-Keuls test (N-K 6) showed that, except for two of the six samples, EW (72%) and EX (72%), all the surfaces were significantly different from each other. See Figure 35. These results are comparable to those of the absorptivity test. Figure 35 also shows increase in abrasion loss with decrease in the rate of evaporation caused by the atmospheric conditions. This, as mentioned earlier, was unexpected.

Effect of Duration of Curing

The analysis of the effect of the three durations of curing at the three relative humidity conditions, shown in ANOVA 7, was carried out according to the layout in Table 13 and Equation 7. Owing to the significance of the interaction of duration with relative humidity, ANOVA 7A was done to

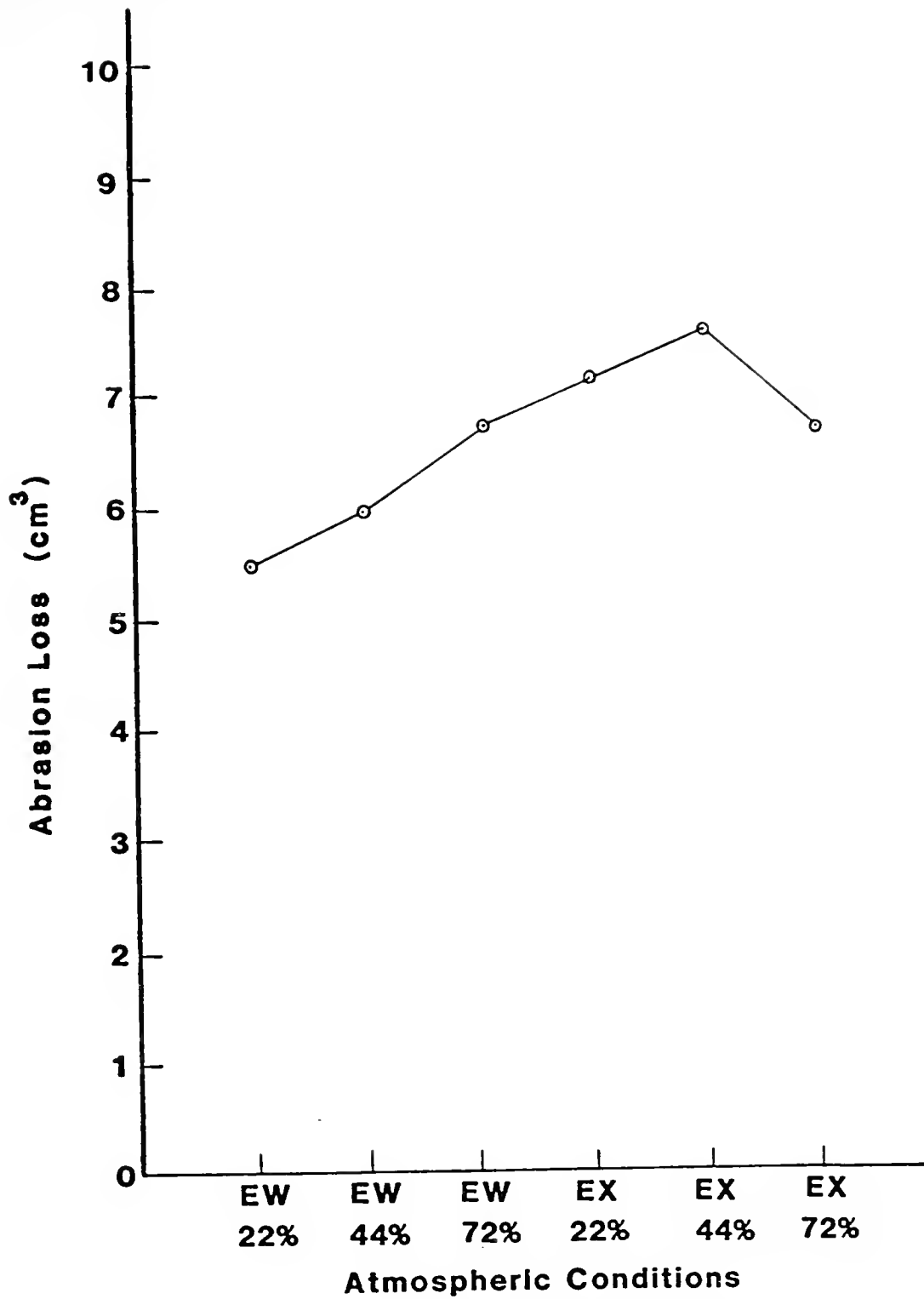


FIG. 35 EFFECT OF ATMOSPHERIC CONDITIONS ON ABRASION LOSS.

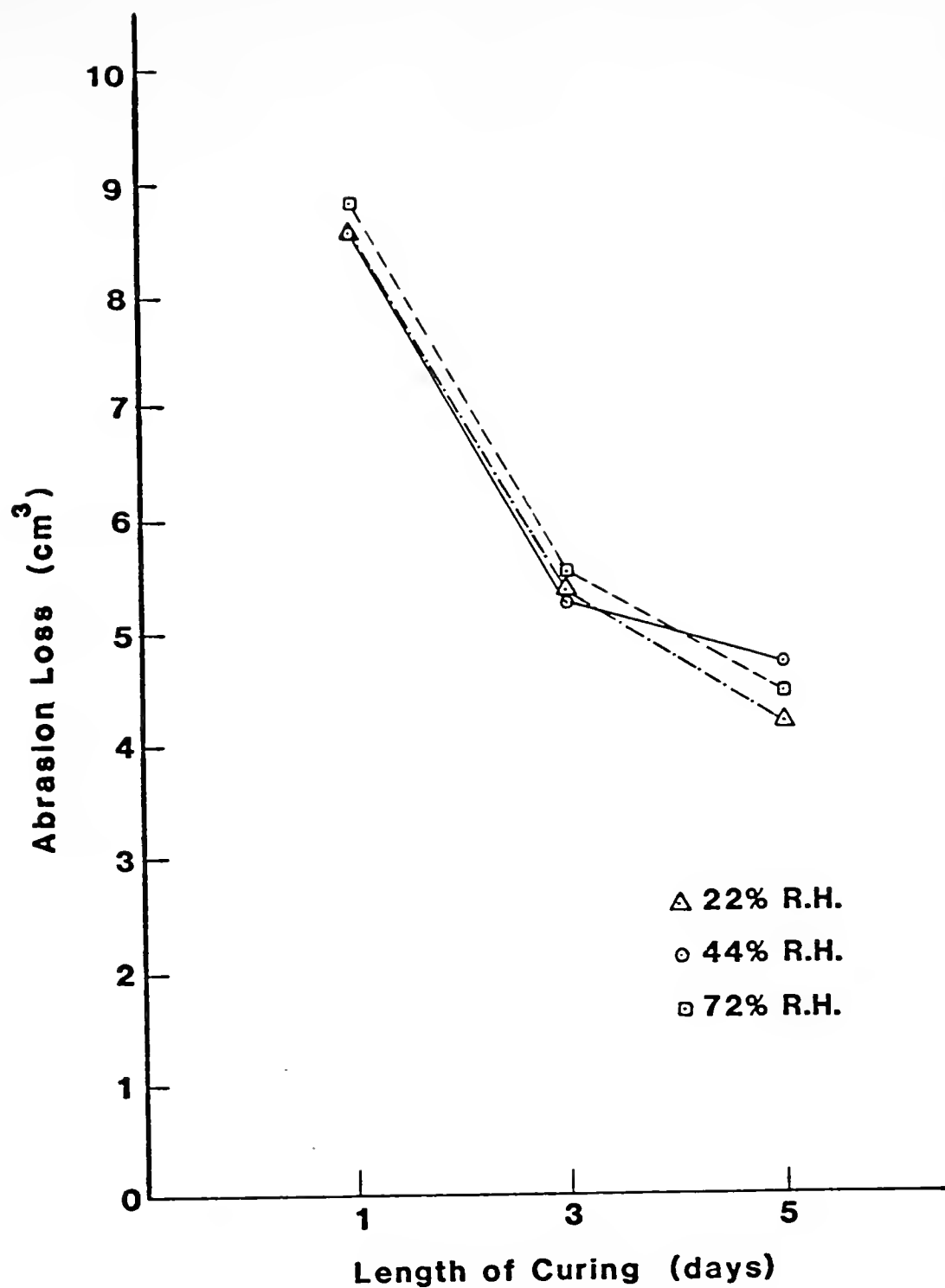


FIG. 36 EFFECT OF RELATIVE HUMIDITY ON ABRASION LOSS FOR SAMPLES MADE OF REGULAR SAND AND CURED WITH WET BURLAP FOR DIFFERENT LENGTHS OF TIME.

examine the effect of duration of curing at each of the three relative humidity conditions. The result indicates that the effect of duration of curing was significant at all three R.H. conditions, and as shown by the Newman-Keuls test N-K 7A, the abrasion losses for the three durations of curing at each of the three R.H. conditions were significantly different from each other. As shown in Figure 36, the effect of age was more pronounced between one and three days than it was between three and five days. This result is to be expected, because the strength gain of concrete is rapid at the beginning and diminishes with time, and abrasion resistance of concrete is most strongly influenced by the strength of the concrete.

Results for Samples Tested at Age 3 Months

The test results for the regular sand samples that were tested three months after the end of their respective curing periods consist of absorptivity tests on the samples initially cured at 22% and 44% relative humidity conditions, and abrasion tests on samples cured at all three R.H. conditions. As stated earlier, the samples were put through cycles of wetting and drying in a manner that was thought to simulate rainy and dry periods. The results will show the effect of the initial curing on the properties of the mortar samples at a later time, after the samples had the opportunity to gain further strength with time and the application of moisture. The non-evaporable water test was not used for

these samples because of its limited usefulness in connection with the samples that were tested soon after the end of their curing periods.

Absorptivity Test Results

In Tables 24 and 25 are presented the test results for the regular sand samples cured under different conditions and durations at the two relative humidity conditions. The analyses of the data were carried out based on modified versions of the layouts on Tables 8-10. The modification involved reducing the relative humidity conditions from three to two. ANOVA 8 is the analysis of the effect of the four methods of curing at the two relative humidity conditions on absorptivity values at the six depths. Owing to the significance of the interaction terms in ANOVA 8, two separate one-way analyses of variance were done first, to examine the effect on absorptivity at 1 cm of the four methods of curing at each of the two R.H. conditions, and second, to determine the variations in absorptivity with depth for each of the four methods of curing. According to ANOVA 8A, the four methods of curing did have a significant effect on the absorptivity at both relative humidity conditions. As shown by N-K 8A, of the four methods, WB and PL produced essentially the same results, and the other two methods produced significantly different effects. This was true for both relative humidity conditions, and in both cases the samples cured with the curing compound had the highest absorptivity values.

Table 24. Absorbivity Test Results for Samples Made of Regular Sand and Initially Cured for 5 Days but Tested at Age 3 Months

Relative Humidity	Curing Condition	$K_a \text{ (x } 10^{-6} \text{ cm}^2/\text{sec)}^*$							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
22%	WB	6.46	0.96	0.77	0.75	0.62	0.66	0.62	0.56
	PL	7.35	2.20	1.63	1.20	0.99	0.96	0.82	0.54
	CC	21.10	19.61	6.34	3.04	2.48	1.91	1.50	1.15
	EX	19.04	5.64	2.60	1.91	1.23	0.99	0.94	0.75
	EW	5.83	1.67	0.99	0.84	0.75	0.70	0.73	0.60
44%	WB	7.14	1.60	0.68	0.66	0.47	0.50	0.49	0.42
	PL	8.07	1.32	0.94	0.86	0.91	0.96	0.79	0.47
	CC	14.11	11.53	5.89	3.08	1.84	1.54	0.89	0.50
	EX	8.89	6.80	1.91	0.99	0.91	0.73	0.84	0.50
	EW	7.14	4.93	2.32	1.70	1.44	1.60	1.44	0.89

*Average of two observations

Table 25. Absorbitivity Test Results for Samples Made of Regular Sand and Initially Cured with Wet Burlap for Different Lengths of Time but Tested at Age 3 Months

Relative Humidity	Curing Duration (Days)	$K_a \text{ (} \times 10^{-6} \text{ cm}^2/\text{sec) } ^*$							
		Depth from Surface (cm)							
		0	1	2	3	4	5	6	7
		0	1	2	3	4	5	6	7
22%	1	8.82	2.28	0.96	0.82	0.75	0.68	0.84	0.77
	3	5.95	1.23	0.77	0.73	0.62	0.66	0.56	0.56
	5	6.46	0.96	0.77	0.75	0.62	0.66	0.62	0.56
44%	1	11.44	3.80	1.18	0.60	0.79	0.58	0.70	0.52
	3	7.56	1.38	0.62	0.56	0.50	0.54	0.50	0.43
	5	7.14	1.60	0.68	0.66	0.47	0.50	0.49	0.42

*Average of two observations

Compared to the absorptivity of the samples that were tested soon after the end of their curing periods, the absorptivity values for these samples were smaller, indicating the extent of further hydration that took place over the three months of wetting and drying. In Table 26 the absorptivity values of the two sets of samples are compared.

Table 26. Comparison of the Absorptivity of the 5-day Old Samples with those Tested at the Age of Three Months, Both Initially Cured at 22% R.H. for 5 Days

Sample	Absorptivity, K_a at 1 cm ($\times 10^{-6}$ cm ² /sec)	
	Tested at age 5 Days	Tested at Age 3 Months
WB5	2.09	0.96
PL5	1.73	2.20
CC5	14.50	19.61
EX5	10.70	5.64
EW5	7.21	1.67

The results presented in Table 26 are interpreted as follows: in the case of the WB5 and PL5 samples where the initial curing was good, the additional time and moisture did not change the absorptivity values significantly, but in the case of the poorly cured samples, the additional moisture improved the surfaces significantly as shown by the reduction of the absorptivity values. The situation with the CC5 samples is interesting because, the ineffective curing compound did not only produce a poor surface, but it reduced the

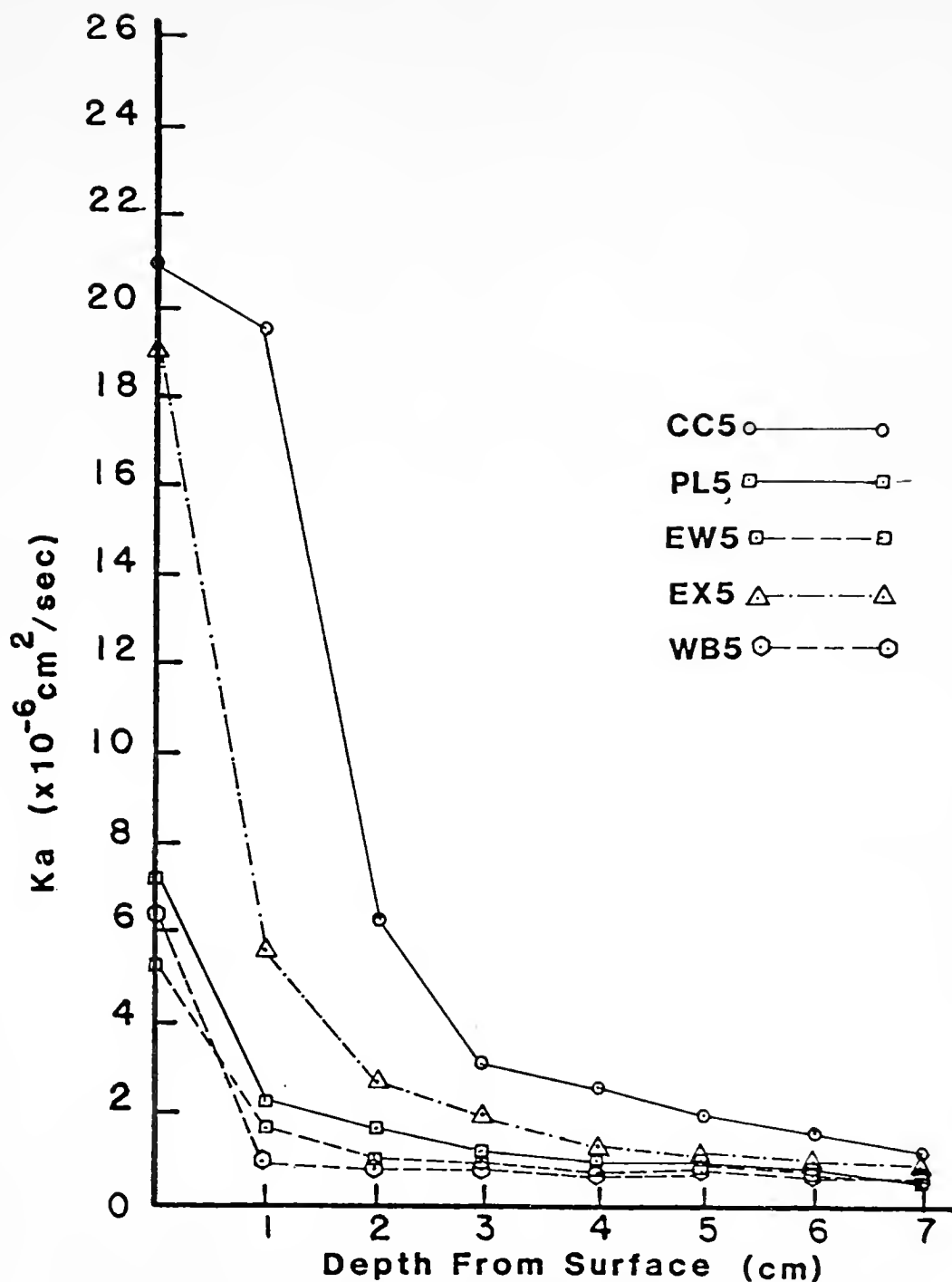


FIG. 37 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR REGULAR SAND SAMPLES CURED AT 22% R.H. AND TESTED AT AGE 3 MONTHS.

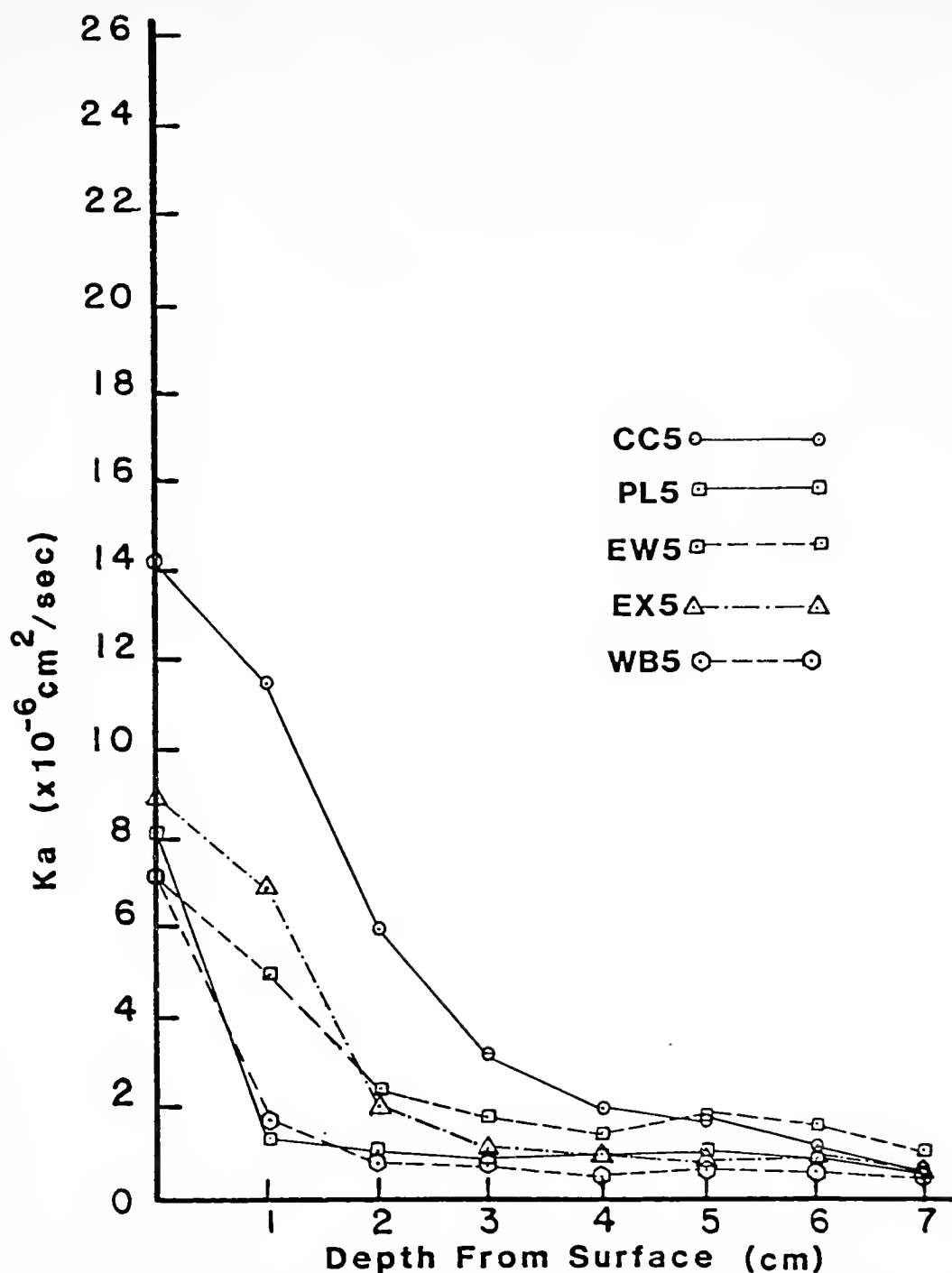


FIG. 38 EFFECT OF DIFFERENT CURING CONDITIONS ON CHANGE IN ABSORPTIVITY WITH DEPTH FOR REGULAR SAND SAMPLES CURED AT 44% R.H. AND TESTED AT AGE 3 MONTHS.

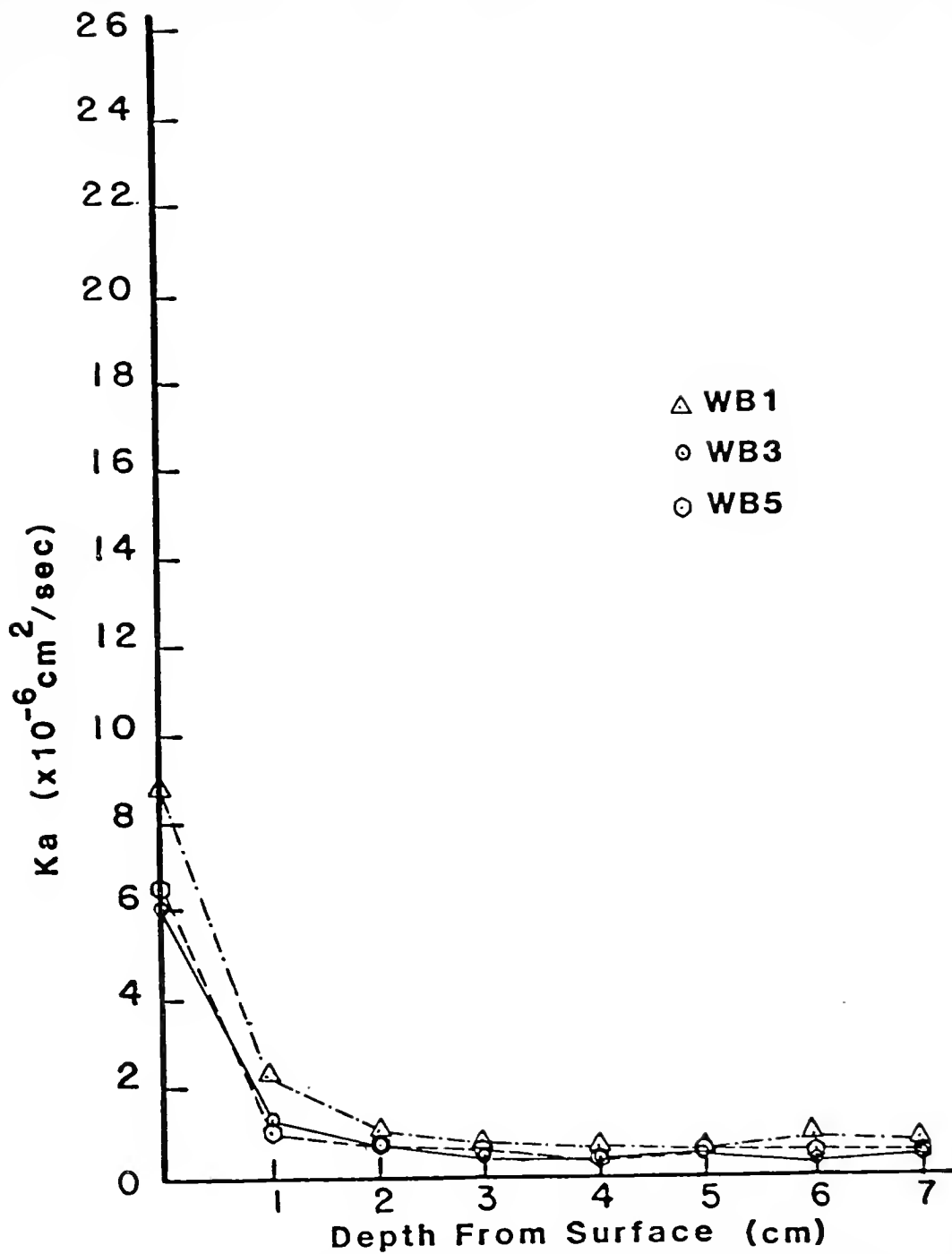


FIG. 39 THE EFFECT OF INITIAL DURATION OF CURING ON ABSORPTIVITY AT AGE 3 MONTHS FOR SAMPLES CURED WITH WET BURLAP AT 22% R.H.

absorption of moisture during the three months, thereby keeping the surface poor. See Figures 37 and 38.

ANOVA 8B in conjunction with N-K 8B shows that the change in absorptivity with depth observed earlier, mainly in the poorly cured samples, was also the case in the 3-month old samples. Comparison of Figure 37 with Figure 10 reveals that the changes in absorptivity with depth for the CC5 and EX5 samples were significant, but in general, the absorptivity values in Figure 37 are lower than those in Figure 10.

An analysis of variance was done to examine the effect of the four atmospheric conditions, i.e., two relative humidity conditions with and without wind, on changes in absorptivity with depth in the 3-month old samples. The result indicated statistically significant effects but further analysis showed that the changes were for all practical purposes unimportant.

Similar analyses were also done to examine the effect of the initial durations of curing on absorptivity at age three months. As shown in Figure 39, after three months, the absorptivities of the three samples were essentially the same. Comparison of Figure 39 with Figure 24 shows the change in absorptivity that took place over the three months.

Abrasion Test Results

In Tables 27 and 28 the abrasion test results for the 3-month old samples are presented. The data were, again, analyzed in the same way as the data for the first set of

Table 27. Abrasion Test Results for Samples Made of Regular Sand and Initially Cured for 5 Days but Tested at Age 3 Months

Relative Humidity	Average Volume of Abraded Cavities (cu cm) for Different Curing Conditions				
	WB5	PL5	CC5	EX5	EW5
22%	3.08	3.41	6.01	3.57	2.88
44%	3.17	3.23	4.20	3.52	3.08
72%	2.98	3.11	4.23	4.42	3.63

Table 28. Abrasion Test Results for Samples Made of Regular Sand and Initially Cured with Wet Burlap for Different Lengths of Time but Tested at Age 3 Months

Relative Humidity	Average Volume of Abraded Cavities (cu cm) for Different Durations of Curing		
	1 Day	3 Days	5 Days
22%	3.20	3.27	3.08
44%	3.66	2.93	3.17
72%	3.60	3.02	2.98

abrasion tests done soon after the end of the curing periods. ANOVA 9 shows the analysis for determining the influence of the initial curing methods at the three relative humidity conditions on the abrasion resistance of the samples three months later. Because the interaction of method by humidity proved to be significant in ANOVA 9, ANOVA 9A was done to examine the effect of method of curing at each of the three relative humidity conditions, and N-K 9A shows differences between the four methods for each relative humidity condition. The conclusions that can be reached from these analyses are: first, differences in abrasion resistance between the well and poorly cured samples were observed three months later although the samples had been given both time and moisture, and secondly, the curing compound which was ineffective to start with reduced the strength development of the samples over the three months. In comparison, the EX and EW samples exhibited a much better abrasion resistance after the three months. Overall there was significant strength gain during the three months as shown by the smaller abrasion losses. Comparison of the values in Table 27 with those in Table 22 shows that clearly.

The effect of the six atmospheric conditions during the initial curing periods disappeared during the three months for all practical purposes. Similarly, the effect of the initial durations of curing were lost during the three months.

Relationships between Absorptivity, Non-evaporable
Water, and Abrasion Resistance

When the three test methods were selected, the idea was to use two of them, absorptivity and non-evaporable water, as measures of the characteristic property of a sample as influenced by the condition and duration of curing, and the abrasion test was to be used as a measure of performance of the sample in service. Therefore, an attempt was made to determine the degree of closeness of the relationship between different pairs of the three variables. The relationships were assumed to be linear, and to find the correlation coefficient for each pair, plots of the data were made, and the least squares method was used to attain the best fit lines.

As shown earlier, the sensitivity of the non-evaporable water test to changes in the mortar samples brought about by the curing conditions and durations was not good, and its usefulness was restricted to detecting changes on account of age. The correlation coefficients for non-evaporable water with absorptivity and with abrasion resistance were also not good (-0.54 and -0.37 respectively). A better correlation was obtained when only the data from the samples used to evaluate the effect of duration of curing were used, but even then the correlation was not satisfactory.

On the other hand, an excellent correlation was observed between the absorptivity at a depth of 1 cm, and the abrasion test results. As shown in Figures 40 and 41, two separate plots were made: one using the data for WB1, WB3 and WB5

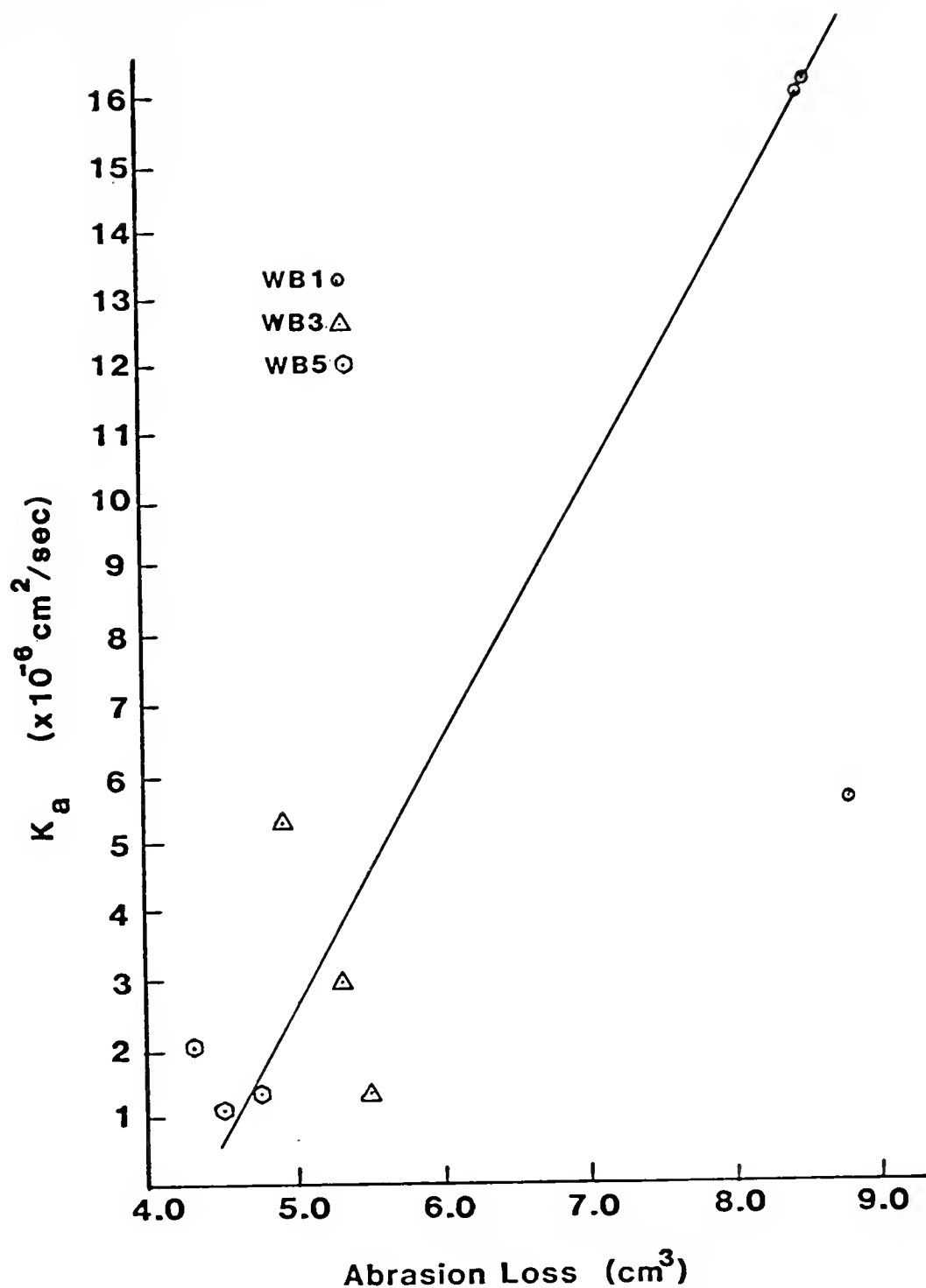


FIG. 40 RELATIONSHIP BETWEEN ABSORPTIVITY AND ABRASION LOSS FOR SAMPLES CURED WITH WET BURLAP FOR DIFFERENT DURATIONS.

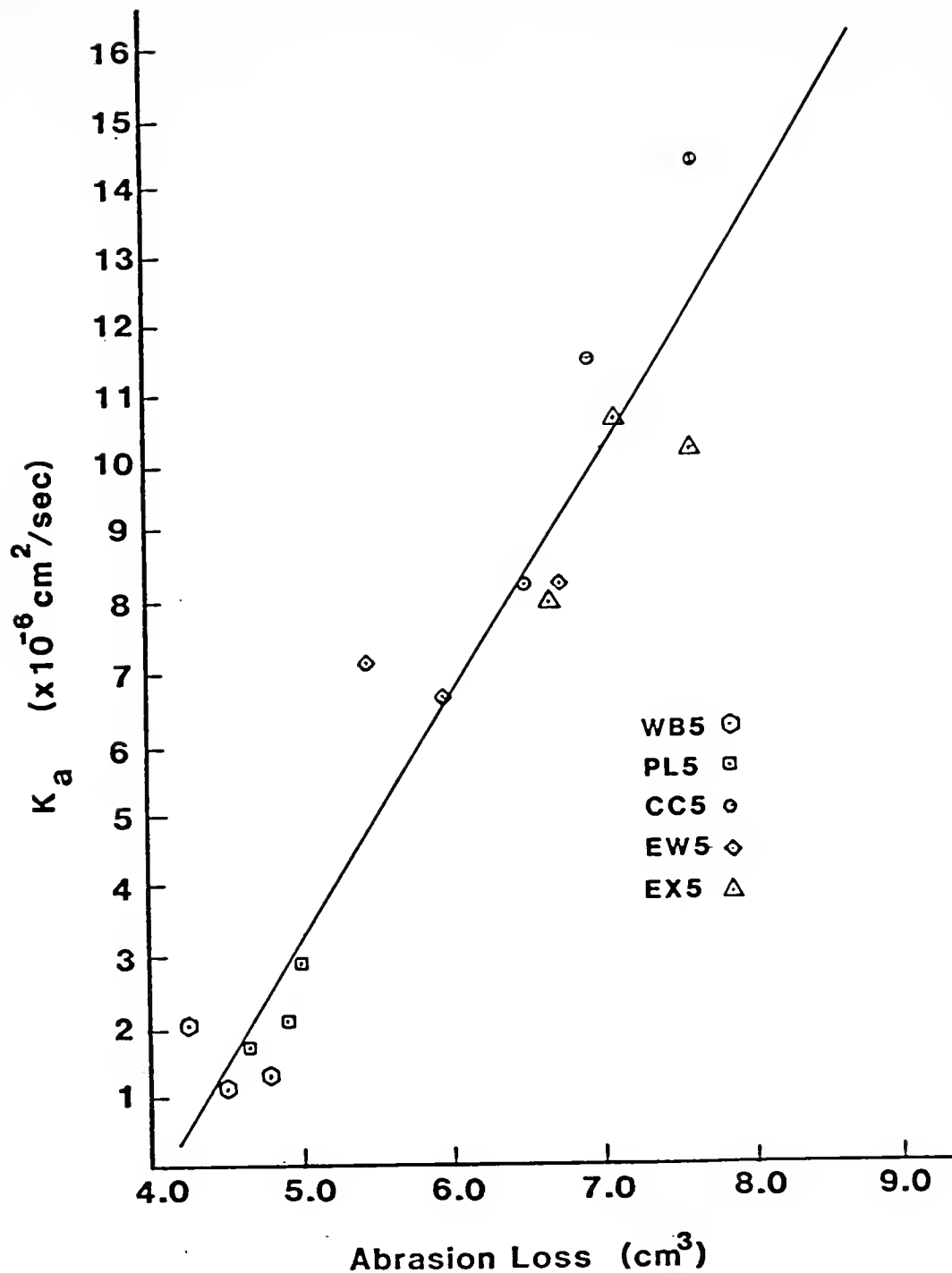


FIG. 41 RELATIONSHIP BETWEEN ABSORPTIVITY AND ABRASION LOSS FOR SAMPLES CURED UNDER DIFFERENT CONDITIONS FOR 5 DAYS.

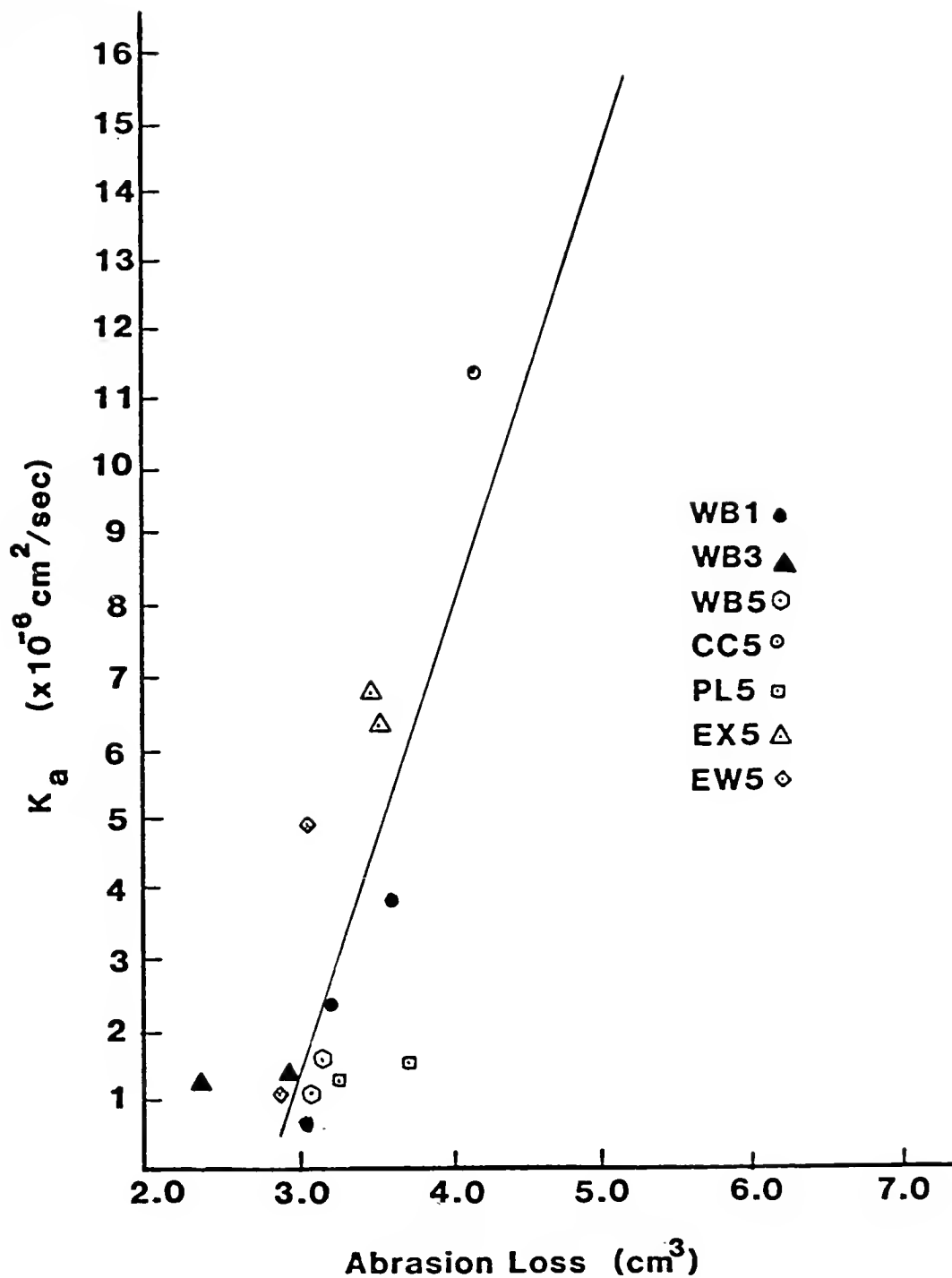


FIG. 42 RELATIONSHIP BETWEEN ABSORPTIVITY AND ABRASION LOSS FOR SAMPLES TESTED AT AGE 3 MONTHS.

samples, and the second, for all five days old samples cured under the various curing conditions. In Figure 40, not including the point corresponding to the highest abrasion loss which was considered to be an outlying observation, the correlation coefficient was determined to be 0.97, and the slope of the line is equal to 3.60. For the data, plotted in Figure 41, the correlation coefficient is 0.96, and the slope of the line is equal to 3.50. Figure 42 is a plot of the data from the samples tested at age three months. The correlation coefficient for those data is 0.95, and the slope of the line is equal to 6.20. The higher slope observed in connection with the three months old samples, may be an indication that the relationship between absorptivity and abrasion resistance is affected by the maturity of the samples.

Distinguishing between Adequate and Inadequate Curing

After identifying a test method sensitive to curing related changes in the mortar samples, the next step was to use the information obtained by the test to draw a quantitative distinction between adequate and inadequate curing. As it turned out, the four methods of curing, basically resulted in samples that could be put into two categories. Curing with wet burlap and with plastic cover produced samples with roughly the same quality of curing as shown by both the absorptivity and abrasion tests, and those samples were put in the "adequately cured" category. On the other hand, the samples cured with the curing compound and with no cover re-

sulted in surfaces with similar qualities, and they were put in the "inadequately cured" category.

In order to devise a way by which one can quantitatively distinguish between the two categories, the absorptivity test results were used. It was thought from the beginning that assigning a certain absorptivity or abrasion resistance value for the surface region of a sample, and saying that value reflects good or poor curing would not be satisfactory. That is because the numbers will change with the mix proportions, air content, and so on. Therefore, taking that approach would require generating values for every conceivable composition of mortar cured in different ways, and that would not be practical. A more reasonable way to quantitatively evaluate the quality of the curing was thought to be by using the changes in absorptivity of a sample in going from the surface into the mass. This approach seems to be applicable regardless of the mix proportions because the effect of curing is pronounced at the surface, and, as shown earlier, it diminishes away from the surface. For the severe atmospheric conditions that produced poor surfaces, it was shown that, in general, the effect of inadequate curing was significant within the first 3 cm from the surface, and below 3 cm the effect was less pronounced.

Using this rationale, formulation of a quantitative distinction between the adequate and inadequate curing was based on differences between absorptivity values at 1 cm and at

6 cm. The differences in absorptivity values for the regular and silica sand samples are presented in Tables 29 and 30 respectively. Separate analyses of variance were done with the data from each of the regular and silica sand samples. The analyses consisted of evaluating the differences between the four methods of curing, at the three relative humidity conditions according to the layouts in Table 8. The depth factor was, of course, absent owing to the use of single values based on differences of absorptivity values from the two different depths. As shown by ANOVA 10 and N-K 10 for the regular sand samples, the effect of method of curing was significant, and of the four methods, WB and PL were the same, and CC and EX were also the same. Thus, the four methods of curing resulted in two distinct types of surfaces, the first pair being good, and the second poor. Interestingly, identical results were obtained from the analyses of the data for the silica sand samples as shown by ANOVA 11 and N-K 11.

Based on differences between the absorptivity values at 1 and 6 cm, it was possible to state with a certain confidence coefficient how much change in absorptivity between the two specified depths would correspond to either adequate or inadequate curing. For the inadequate curing, the interest was on the lowest difference in absorptivity because large differences would definitely point to poor curing. On the other hand, for what was considered to be adequate curing, the focus was on the maximum difference because small

Table 29. Differences between Absorptivity Values at Depths 1 and 6 cm for Samples Made of Regular Sand

Curing Condition	22%		44%		72%	
	Core		Core		Core	
	1	2	1	2	1	2
WB5	1.58	0.35	0.68	0.54	0.22	0.53
PL5	0.40	1.03	1.77	0.40	1.88	2.29
CC5	14.87	12.64	9.69	11.52	10.32	3.90
EX5	7.73	7.91	8.22	10.03	6.47	7.38

Table 30. Differences between Absorptivity Values at Depths 1 and 6 cm for Samples Made of Silica Sand

Curing Condition	22%		44%		72%	
	Core		Core		Core	
	1	2	1	2	1	2
WB5	0.51	0.45	0.69	0.39	0.14	0.36
PL5	1.05	1.57	2.11	0.62	1.55	2.18
CC5	17.33	11.06	14.58	14.49	4.76	8.26
EX5	12.50	8.66	5.33	9.01	4.98	7.18

differences would imply good curing. Therefore, the need was for one-sided confidence limits.

The confidence interval for a mean, μ , with a confidence coefficient of $1 - \alpha$ is obtained by the following (43 p. 12):

$$\bar{y} - t(1-\alpha/2; \text{d.f.}) s_{\bar{y}} < \mu < \bar{y} + t(1-\alpha/2; \text{d.f.}) s_{\bar{y}} \quad (8)$$

where

\bar{y} = the sample mean

$t(1-\alpha/2; \text{d.f.})$ = the $(1-\alpha/2)^{\text{th}}$ percentile of the t distribution with a given degrees of freedom, d.f., of the error term

$s_{\bar{y}}$ = the standard error of the mean

and $s_{\bar{y}} = \sqrt{\frac{\text{MS error}}{n}}$

where

MS error = mean square error obtained from the ANOVA tables

and n = number of observations per mean

As stated above, for the problem on hand, the interest was in a one sided confidence coefficient. Therefore, for α of 0.05 Equation 8 gives a one-sided 97.5% confidence coefficient.

For the regular sand samples, using the information from ANOVA 10,

$$s_{\bar{y}} = \sqrt{\frac{2.41}{2}} = 1.09$$

and $t(0.975; 12) = 2.179$

To set the limit for the adequate curing category, the difference between the absorptivity values of 1 and 6 cm for the PL5 sample was used. The WB5 sample which was also considered to be in the adequate curing category had smaller difference in the absorptivity values, but because the interest was on the largest difference that would indicate good curing, the value for the PL5 sample was selected. Based on that, it can be stated with a 97.5% confidence that a difference in absorptivity as high as $1.295 + (2.179)(1.09)$, which is equal to 3.69 could be indicative of good or adequate curing. For the limit that represented inadequate curing, the interest was in the smallest difference, and the value from the EX5 sample was used. The 97.5% confidence limit for the poor curing category was $7.957 - (2.179)(1.09)$, which is 5.57.

Using the data and analysis for the silica sand samples the following 97.5% confidence limits were obtained:

$$\text{for adequate curing, } 1.513 + (2.179)(1.09) = 3.90$$

$$\text{and for inadequate curing, } 7.943 - (2.179)(1.09) = 5.55$$

The results from the regular and silica sand samples are nearly the same. The conclusion would then be, a difference of $\leq 3.7 \times 10^{-6} \text{ cm}^2/\text{sec}$ between the absorptivity values at 1 and 6 cm was indicative of adequate curing, and a difference of $\geq 5.5 \times 10^{-6} \text{ cm}^2/\text{sec}$ corresponded to poor curing for the five days old samples.

According to these criteria all of the WB5 and PL5 samples can be put in the adequately cured category, and all of the CC5 and EX5 samples were inadequately cured.

SUMMARY OF RESULTS

The following is a summary of the major findings of this study:

1. The absorptivity test was proven to be a sensitive measure of curing-related changes in the pore structure of the mortar samples.

- (a) The four methods of curing at the 22% and 44% R.H. conditions produced significantly different absorptivity values, and at the 72% R.H. condition the differences were still significant, but to a lesser degree. This finding shows the importance of proper curing, even for the relatively mild atmospheric condition where the temperature was 81°F (27°C), the relative humidity 72%, and no wind.
- (b) There were significant changes in absorptivity with depth for the samples cured with the curing compound and for those with no cover, but for the other two curing methods (wet burlap and plastic cover) the changes in ab-

sorptivity with depth were not significant.

- (c) The six atmospheric conditions did not produce significantly different absorptivity values, but there were significant variations in absorptivity with depth in the uncovered samples. The six atmospheric conditions may not have actually been as different in their severity as expected. In fact, at each of the three relative humidity conditions, the samples that were exposed to wind (EW) had less absorptive and stronger surfaces than those left uncovered without wind (EX).
- (d) The effect of duration of curing on absorptivity for the samples that were cured for different lengths of time was significant, but there was no significant change in absorptivity with depth for all three durations of curing except in the one day old samples. For reasons that are not apparent, the one day old samples produced absorptivity values that changed with depth.

2. From the plots of absorptivity versus depth it was observed that the zone affected by the poorest curing conditions extended approximately 3 cm into the slabs.

3. The absorptivity test results from the silica sand samples were similar to those from the regular sand samples, although the air contents and air systems in the two samples were markedly different. The silica sand samples contained more entrapped air, and a large number of the air bubbles were irregular in shape and large compared to the size of the test specimens. Therefore, the data from the silica sand samples had more scatter, but the similarity in the results from the two types of samples is thought to be an indication of the reliability and effectiveness of the absorptivity test.

4. The abrasion test was also found to be sensitive to the curing conditions and durations, and it correlated well with the findings from the absorptivity test. Except for minor deviations, the results from the absorptivity test and those from the abrasion test conveyed the same story.

5. The non-evaporable water test was found to be not as useful as expected for evaluating the extent of cement hydration as affected by the curing of the mortar samples.

- (a) The four methods of curing at the three R.H. conditions did not produce different results in the non-evaporable water test.

- (b) Contrary to what was expected, there were no significant and consistent changes in the non-evaporable water content of the various layers of even the most poorly cured samples.
- (c) The six atmospheric conditions did not produce different results consistently.
- (d) The test was found to be sensitive to the three durations of curing. It also produced different results at the three R.H. conditions for a given method of curing.
- (e) The results from both the regular and silica sand samples were similar, although the temperatures used to drive off the non-evaporable water were different.

6. The absorptivity and abrasion tests done on the samples that were tested three months after their respective curing periods revealed that the initial methods of curing did have an effect on the properties of the mortar samples three months later, but the effects of the six atmospheric conditions and the three durations of curing were lost during the three months period. All the samples except those cured

with the curing compound gained significant strength during the three months of wetting and drying. The curing compound was found to be detrimental in the long run, although it was merely ineffective initially.

7. Excellent correlation was found between the abrasion test and the absorptivity test; the relationship was slightly different in the case of the three month old samples.

8. A method for distinguishing between adequate and inadequate curing based on differences in absorptivity values at depths of 1 and 6 cm is suggested for the five days old samples. With a 97.5% confidence, a difference of $\leq 3.7 \times 10^{-6} \text{ cm}^2/\text{sec}$ was found to indicate adequate curing, and a difference of $\geq 5.5 \times 10^{-6} \text{ cm}^2/\text{sec}$ was an indication of inadequate curing. These figures were found to be the same for both the regular and silica sand samples.

CONCLUSIONS

Based on the results of this study, the following conclusions seem reasonable.

1. The absorptivity test is a sensitive, simple, and quick measure of curing-related changes in the pore structure of the paste in the mortar samples. And it is reasonable, by logical inference, to assume that the test can be made applicable to assessing curing quality of concrete.

2. Poorly cured slabs exhibit a significant change in absorptivity with depth, i.e., a much higher absorptivity occurs at the surface compared to the absorptivity at greater depth in the slabs. For well cured slabs the change in absorptivity with depth is small.

3. As determined by the absorptivity test, and for the worst atmospheric and curing conditions encountered in this study, the zone of a slab that is influenced by the curing is approximately the top 3 cm.

4. Determination of non-evaporable water content is not a sensitive measure of curing-related changes in the paste structure.

5. The abrasion test, according to ASTM C418, is a sensitive indicator of the surface strength of mortar, as affected by the curing.

6. The effects of initial poor curing can be detected as long as three months later, even if the mortar is wetted intermittently (as was done in this study) during the three months.

7. Distinction between adequately and inadequately cured mortar samples can be made based on differences in absorptivity values at depths of 1 and 6 cm. This method was shown to work for the five-day-old samples, but the indications are that it can be applied to both older and younger samples.

8. The method of using absorptivity differences for evaluating the quality of curing has the potential for evaluating the effectiveness of curing materials. The attractiveness of this method comes from the fact that the effectiveness of the curing medium would be based on the response of the mortar itself, and the curing can be done in any desired atmospheric condition rather than a standard one that may not be related to actual conditions in which the curing may take place.

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APPENDIX

This appendix contains the ANOVA tables and the Newman-Keuls analyses in the order they were mentioned in the text. All significance tests were done at the 5% level.

ANOVA 1

Source	d.f.	Mean Square (M.S.)	F
Method, M_i	3	76.48	72.63*
Humidity, H_j	2	17.73	16.83*
Depth, D_l	5	88.06	193.17*
MH_{ij}	6	4.97	4.72*
MD_{il}	15	21.10	46.29*
HD_{jl}	10	1.25	2.74*
Core, $C_{(ij)k}$	12	1.05	
MHD_{ijl}	30	0.96	2.12*
$CD_{(ij)kl}$	60	0.46	

ANOVA 1A

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
Method, M_i	3	84.85	137.38*	57.27	55.49*	27.17	5.34
Core, $C_{(i)k}$	4	0.62		1.03		5.08	

*Significant at the 5% level.

N-K 1A

Table of Differences between Means

For 22% R.H. condition:

<u>Rank</u>	<u>PL</u>	<u>WB</u>	<u>EX</u>
CC	13.18*	12.81*	4.24*
EX	8.94*	8.57*	
WB	0.38		

For 44% R.H. condition:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	10.29*	9.49*	1.38
EX	8.91*	8.11*	
PL	0.80		

*Significant at the 5% level.

ANOVA 1B

For WB5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
Depth, (D_1)	5	0.27	3.44	0.11	6.25*	0.03	0.55
Core, ($C_{(1)k}$)	6	0.08		0.02		0.06	

For PL5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
D_1	5	0.16	1.71	0.32	1.59	1.10	32.39*
$C_{(1)k}$	6	0.09		0.20		0.03	

For CC5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
D_1	5	52.17	154.37*	34.46	60.04*	15.34	4.20 ¹
$C_{(1)k}$	6	0.34		0.57		3.65	

¹It is unrealistically low because the M.S. error is too high on account of one of the two observations being too low.

For EX5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
D_1	5	18.57	81.86*	23.34	39.42*	13.78	17.23*
$C_{(1)k}$	6	0.23		0.59		0.80	

*Significant at the 5% level.

N-K 1B

Table of Differences between Means

For CC5 @ 22% R.H.:

<u>Rank</u>	<u>6 cm</u>	<u>5 cm</u>	<u>4 cm</u>	<u>3 cm</u>	<u>2 cm</u>
1 cm	13.76*	13.16*	11.76*	10.89*	8.18*
2 cm	5.58*	4.98*	3.58*	2.71*	
3 cm	2.87*	2.28*	0.88		
4 cm	1.99*	1.40			
5 cm	0.59				

For EX5 @ 22% R.H.:

<u>Rank</u>	<u>6 cm</u>	<u>5 cm</u>	<u>4 cm</u>	<u>3 cm</u>	<u>2 cm</u>
1 cm	7.82*	7.81*	7.57*	6.77*	5.03*
2 cm	2.80*	2.79*	2.55*	1.75*	
3 cm	1.05	1.04	0.80		
4 cm	0.25	0.24			
5 cm	0.01				

*Significant at the 5% level.

ANOVA 2

Source	d.f.	M.S.	F
Atmospheric Conditions, A_i	5	7.39	4.22
Depth, D_k	5	78.64	124.53*
Core, $C_{(i)j}$	6	1.75	
AD_{ik}	25	1.05	1.67
$CD_{(i)jk}$	30	0.63	

ANOVA 3

Source	d.f.	M.S.	F
Duration, T_i	2	678.74	684.68*
Humidity, H_j	2	166.87	168.33*
Depth, D_l	5	21.15	62.51*
TH_{ij}	4	83.21	83.94*
TD_{il}	10	8.27	24.44*
HD_{jl}	10	2.48	7.33*
Core, $C_{(ij)k}$	9	0.99	
THD_{ijl}	20	1.04	3.06*
$CD_{(ij)kl}$	45	0.33	

*Significant at the 5% level.

ANOVA 3A

Source	d.f.	For WB1		For WB3		For WB5	
		M.S.	F	M.S.	F	M.S.	F
H_j	2	69.88	51.31*	6.74	48.23*	0.52	3.02
$C_{(j)k}$	3	1.36		0.14		0.17	

ANOVA 4

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
Duration, T_i	2	0.25	47.61*	0.36	75.31*	0.32	26.33*
Core, $C_{(i)k}$	3	0.005		0.005		0.01	

*Significant at the 5% level.

N-K 4

Table of Differences between Means

For 22% R.H.:

<u>Rank</u>	<u>1 day</u>	<u>3 days</u>
5 days	0.70*	0.22
3 days	0.48*	

For 44% R.H.:

<u>Rank</u>	<u>1 day</u>	<u>3 days</u>
5 days	0.84*	0.36*
3 days	0.48*	

For 72% R.H.:

<u>Rank</u>	<u>1 day</u>	<u>5 days</u>
3 days	0.73*	0.07
5 days	0.66*	

*Significant at the 5% level.

ANOVA 5

Source	d.f.	M.S.	F
Method, M_i	3	46.36	437.58*
Humidity, H_j	2	1.30	12.28*
MH_{ij}	6	1.31	12.35*
Observation, $O_{(ij)k}$	84	0.11	

ANOVA 5A

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
M_i	3	23.11	162.35*	16.43	219.79*	9.45	93.67*
$O_{(i)k}$	28	0.14		0.07		0.10	

*Significant at the 5% level.

N-K 5A

Table of Differences between Means

For 22% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	3.37*	2.99*	0.55*
EX	2.82*	2.45*	
PL	0.37		

For 44% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>CC</u>
EX	2.83*	2.71*	0.66*
CC	2.17*	2.04*	
PL	0.12		

For 72% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>CC</u>
EX	2.19*	1.66*	0.17
CC	2.02*	1.49*	
PL	0.53*		

ANOVA 6

Source	d.f.	M.S.	F
Atmospheric Conditions, A_i	5	4.71	54.74*
Observations, $O_{(i)j}$	42	0.09	

*Significant at the 5% level.

N-K 6

<u>Rank</u>	<u>EW(22%)</u>	<u>EW(44%)</u>	<u>EX(72%)</u>	<u>EW(72%)</u>	<u>EX(22%)</u>
EX(44%)	2.13*	1.63*	0.94*	0.82*	0.51*
EX(22%)	1.62*	1.12*	0.43*	0.31*	
EW(72%)	1.31*	0.81*	0.12		
EX(72%)	1.19*	0.69*			
EW(44%)	0.49*				

ANOVA 7

<u>Source</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Duration, T_i	2	113.56	2721.66*
Humidity, H_j	2	0.23	5.51*
TH_{ij}	4	0.28	6.72*
Observation, $O_{(ij)k}$	63	0.04	

ANOVA 7A

<u>Source</u>	<u>d.f.</u>	<u>@ 22% R.H.</u>		<u>@ 44% R.H.</u>		<u>@ 72% R.H.</u>	
		<u>M.S.</u>	<u>F</u>	<u>M.S.</u>	<u>F</u>	<u>M.S.</u>	<u>F</u>
T_i	2	39.09	78.19*	33.63	762.95*	41.39	1445.0*
$O_{(i)k}$	21	0.05		0.04		0.03	

*Significant at the 5% level.

N-K 7A

Table of Differences between Means

For 22% R.H.:

<u>Rank</u>	<u>5 days</u>	<u>3 days</u>
1 day	4.27*	3.13*
3 days	1.15*	

For 44% R.H.:

<u>Rank</u>	<u>5 days</u>	<u>3 days</u>
1 day	3.79*	3.26*
3 days	0.53*	

For 72% R.H.:

<u>Rank</u>	<u>5 days</u>	<u>3 days</u>
1 day	4.35*	3.32*
3 days	1.04*	

ANOVA 8

<u>Source</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Method, M_i	3	87.53	335.35*
Humidity, H_j	1	7.46	28.60*
Depth, D_l	5	66.95	315.56*
MH _{ij}	3	3.50	13.41*
MD _{il}	15	23.77	112.06*
HD _{jl}	5	1.56	7.35*
Core, $C_{(ij)k}$	8	0.26	
MHD _{ijl}	15	3.03	14.27*
CD _{(ij)kl}	40	0.21	

*Significant at the 5% level.

ANOVA 8A

Source	d.f.	@ 22% R.H.		@ 44% R.H.	
		M.S.	F	M.S.	F
M_i	3	146.48	170.56*	47.14	42.41*
$C_{(i)k}$	4	0.86		1.11	

N-K 8A

For 22% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	18.65*	17.36*	13.93*
EX	4.73*	3.44*	
PL	1.29		

For 44% R.H.:

<u>Rank</u>	<u>PL</u>	<u>WB</u>	<u>EX</u>
CC	10.21*	9.95*	4.73*
EX	5.48*	5.22*	
WB	0.27		

ANOVA 8B

For WB5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.	
		M.S.	F	M.S.	F
D_1	5	0.030	11.57*	0.37	27.34*
$C_{(1)k}$	6	0.003		0.01	

*Significant at the 5% level.

For PL5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.	
		M.S.	F	M.S.	F
D_1	5	0.58	3.63	0.07	1.11
$C_{(1)k}$	6	0.16		0.06	

For CC5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.	
		M.S.	F	M.S.	F
D_1	5	97.30	627.25*	32.68	42.70*
$C_{(1)k}$	6	0.16		0.77	

For EX5:

Source	d.f.	@ 22% R.H.		@ 44% R.H.	
		M.S.	F	M.S.	F
D_1	5	6.57	12.39*	11.29	156.72*
$C_{(1)k}$	6	0.53		0.07	

N-K 8B

Table of Differences between Means

For WB5 at 22% R.H.:

<u>Rank</u>	<u>6 cm</u>	<u>4 cm</u>	<u>5 cm</u>	<u>3 cm</u>	<u>2 cm</u>
1 cm	0.34*	0.34*	0.30*	0.22*	0.20*
2 cm	0.14	0.14	0.10	0.02	
3 cm	0.12	0.12	0.08		
5 cm	0.04	0.04			
4 cm	0.00				

*Significant at the 5% level.

For CC5 at 22% R.H.:

<u>Rank</u>	<u>6 cm</u>	<u>5 cm</u>	<u>4 cm</u>	<u>3 cm</u>	<u>2 cm</u>
1 cm	18.11*	17.69*	17.13*	16.59*	13.31*
2 cm	4.81*	4.38*	3.83*	3.29*	
3 cm	1.52*	1.09	0.54		
4 cm	0.98	0.56			
5 cm	0.43				

For EX5 at 22% R.H.:

<u>Rank</u>	<u>6 cm</u>	<u>5 cm</u>	<u>4 cm</u>	<u>3 cm</u>	<u>2 cm</u>
1 cm	4.75*	4.69*	4.46*	3.77*	3.04*
2 cm	1.72	1.66	1.43	0.74	
3 cm	0.98	0.92	0.69		
4 cm	0.29	0.23			
5 cm	0.06				

*Significant at the 5% level.

Similar responses were observed for the four methods of curing at the 44% R.H. condition.

ANOVA 9

<u>Source</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Method, M_i	3	14.81	304.30*
Humidity, H_j	2	2.04	41.24*
MH_{ij}	6	2.97	61.09*
Observation, $O_{(ij)k}$	84	0.05	

ANOVA 9A

Source	d.f.	@ 22% R.H.		@ 44% R.H.		@ 72% R.H.	
		M.S.	F	M.S.	F	M.S.	F
M_i	3	14.45	238.66*	1.81	47.00*	4.50	95.65*
$O_{(i)k}$	28	0.07		0.04		0.05	

N-K 9A

Table of Differences between Means

At 22% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	2.93*	2.60*	2.44*
EX	0.49*	0.16	
PL	0.33*		

*Significant at the 5% level.

At 44% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	1.04*	0.97*	0.68*
EX	0.36*	0.29*	
PL	0.07		

At 72% R.H.:

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>CC</u>
EX	1.45*	1.32*	0.19
CC	1.25*	1.13*	
PL	0.13		

ANOVA 10

<u>Source</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Method, M_i	3	142.99	59.43*
Humidity, H_j	2	6.11	2.54
MH_{ij}	6	6.54	2.72
Core, $C_{(ij)k}$	12	2.41	

N-K 10

Table of Differences between Means

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	9.84*	9.19*	2.53
EX	7.31*	6.66*	
PL	0.65		

*Significant at the 5% level.

ANOVA 11

<u>Source</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Method, M_i	3	173.24	47.39*
Humidity, H_j	2	19.06	5.21*
MH_{ij}	6	11.13	3.00
Core, $C_{(ij)k}$	12	3.66	

N-K 11

Table of Differences between Means

<u>Rank</u>	<u>WB</u>	<u>PL</u>	<u>EX</u>
CC	11.32*	10.23*	3.80
EX	7.52*	6.43*	
PL	1.09		

*Significant at the 5% level.

